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Altitude as a Factor in Air Pollution

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Air pollution is affected by change in altitude. Cities with surface elevations above 1500 meters have atmospheric pressures which are approximately fifteen percent (15%) below pressures at sea level. Consequently, mobile sources designed to operate at pressures of one atmosphere perform less efficiently at high altitudes and emit greater amounts of hydrocarbons and carbon monoxide than those designed to operate at the lower atmospheric pressures. The net result is a photochemical smog problem which is further enhanced by the increased solar radiation of higher altitudes.

The most significant effect of air pollution at high altitudes is upon human health. This is due primarily to the inhalation of carbon monoxide at the reduced oxygen concentrations of high altitudes. Particularly susceptible is the fetus exposed to hypoxia and elevated carboxyhemoglobin levels. There is insufficient evidence to support significantly increased ecological effects at high altitudes.

Reduction in visibility is being observed in the vicinity of large metropolitan areas and near large industrial complexes at high altitudes.

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ALTITUDE AS A FACTOR IN AIR POLLUTION

ENVIRONMENTAL CRITERIA AND ASSESSMENT OFFICE
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

PREFACE

This document has been prepared in response to a request by EPA Region VIII.

The major objective of the document is to provide a state-of-knowledge report on the differential effects caused by higher altitudes upon air pollution and related activities. Although preparation of this report has required a review and evaluation of current scientific knowledge regarding altitude effects on air pollution, the document does not constitute an in-depth scientific review.

A separate report to Congress is in preparation by Emissions Control Technology Division (ECTD) at Ann Arbor for release October 1, 1978, in response to the Clean Air Act Amendments of 1977. In contrast to the economic impact and technological feasibility for separate high altitude standards to be discussed in the report to Congress, the following document presents a general overview of altitude effects on pollution.

The Agency acknowledges efforts and contributions of all persons who have participated as authors and reviewers of this document.

ABSTRACT

Air pollution is affected by change in altitude. Cities with surface elevations above 1,500 meters have atmospheric pressures which are approximately fifteen percent (15%) below pressures at sea level. Consequently, mobile sources designed to operate at pressures of one atmosphere perform less efficiently at high altitudes and emit greater amounts of hydrocarbons and carbon monoxide than those designed to operate at the lower atmospheric pressures. The net result is a photochemical smog problem which is further enhanced by the increased solar radiation of higher altitudes.

The most significant effect of air pollution at high altitudes is upon human health. This is due primarily to the inhalation of carbon monoxide at the reduced oxygen concentrations of high altitudes. Particularly susceptible is the fetus exposed to hypoxia and elevated carboxyhemoglobin levels. There is insufficient evidence to establish significantly increased ecological effects at high altitudes. Reduction in visibility is being observed in the vicinity of large metropolitan areas and near large industrial complexes at high altitudes.

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I. SUMMARY

Few air pollution studies have been performed in which altitude (surface elevation above sea level) and associated atmospheric properties (pressure, temperature, density, solar radiation) have been treated as independent variables. Notable exceptions are the studies involving the health effects of carbon monoxide (CO) under hypobaric conditions. The results of these studies indicate that the effects of CO exposure and of hypoxia induced by high altitude are similar and suggest that when high altitude and CO exposure are combined, the effects are additive. *In vivo,* there is an interaction between these two factors such that exposure to one may induce a physiological response that influences the response of the body to the other.

Significant alterations in alveolar ventilation occur at high altitudes. This results in higher aero-toxicant dosage, especially for particulate or gaseous pollutants produced in closed spaces. Absorption and translocation of aero-toxicants may be affected by changes in altitude; however, experiments have not been performed to confirm this.

Very few studies have been performed regarding the effects of air pollution as a function of altitude on ecosystems. The available data are inconclusive; however, they suggest that at least certain ecosystem components may be more sensitive to air pollutants at altitudes above approximately 2,500 m.

Emissions from mobile sources are directly related to changes in atmospheric density, hence changes in altitude. Other factors being equal, most vehicles will emit more hydrocarbons and carbon monoxide and less oxides of nitrogen as the altitude increases. Normally, the amount of hydrocarbons and CO in diesels will increase with altitude. Changes in fuel-air mixtures and fuel composition may partially compensate for the change in altitude.

The efficiency of combustion will normally decrease with an increase in altitude. This factor, coupled with lower air viscosity at higher altitudes, may affect particulate concentrations in the vicinity of stationary sources located at higher altitudes. However, the effect is thought to be small compared to other factors due to the decrease in atmospheric density.

Altitude is a significant factor in ambient air pollution monitoring. Changes in ambient atmospheric pressure directly affect the volume of air sampled. Most techniques and devices are designed for operation at standard sea level pressure of 760 torr. Failure to correct for a change in elevation to 1,525 m (5,000 feet) may result in an error of approximately 15 percent in volume, hence concentration. Historically, the National Air Surveillance Network (NASN) has made *no correction* for differing atmospheric pressures at the various sites in its network. Calibration methods are affected by changes in altitude and care must be exercised to minimize this effect.

The two most common units of measurement of air pollutants, micrograms per cubic meter ($\mu g/m^3$) and parts per million (ppm), are both affected by changes in altitude, but in different ways. Unless volumes of air sampled are corrected to a reference pressure and temperature, the calculated value of the mass of pollutant per unit volume of air sampled will vary with the altitude of the sampling site. Exposure to identical parts per million concentration at differing pressures does not expose the receptor to identical numbers of moles of pollutant per unit volume of air, since the conversion is a function of pressure. The implication of this altitude effect on pollutant exposure data may not be widely appreciated.

Important properties of the atmosphere (pressure, temperature, density, solar radiation, wind, stability) vary significantly with altitude. These properties, coupled with the chemistry of the medium, characterize the behavior of the atmospheric boundary layer. It is logical to conclude that the behavior of pollutants emitted to the atmosphere will be influenced by variations in altitude. For example, reduction in visibility is being observed in the vicinity of large metropolitan areas and near large industrial complexes. Also, differences in altitude may account for a portion of the variance observed between different urban atmospheres. Since altitude is only one of many variables in a complex system, the question of significance is one of degree.

II. ENVIRONMENTAL RELATIONSHIPS

EFFECTS OF ALTITUDE ON THE ATMOSPHERE

Introduction

The purpose of this document is to discuss the state of knowledge of the effects of altitude (surface elevation above sea level) on the production, dispersion, and potential effects of air pollution. There are four urban areas in the United States above 1,300 m and with populations greater than 200,000: Denver, Salt Lake City, Albuquerque, and Colorado Springs. The types and degree of air pollution vary considerably across the United States. The main factors causing the differences are source emissions, chemical reactions in the free atmosphere, meteorology, and topography. Altitude may also play a role in determining the degree of pollution.

The meteorological and climatic conditions of a given region are related to its geographical location and local topography. Location determines the large scale weather influences that dominate a region, and topography alters air flow and thermal structure of the atmosphere which may increase or restrict the dispersion of air pollutants. Over the western United States and in parts of the eastern United States, climates change rapidly even within very short distances due to the terrain and the variations in altitude. A change in all climatic parameters is related to changes in altitude. This is true, of course, for the free atmosphere as well as for different land elevations. In general, as the elevation of the land increases above mean sea level, there is a decrease in atmospheric pressure, a decrease in temperature, an increase of wind speed and an increase of solar radiation. As altitude increases there is a complex effect on the distribution of cloudiness, precipitation, and pollutants.

The effects of variations in ambient air temperature, pressure, solar radiation and wind speed caused by increased altitude on production and dispersion of either primary or secondary pollutants may be either direct or indirect.

General Climatology

The weather at a given place is the sum total of all meteorological variables, such as solar radiation, temperature, pressure, wind, precipitation, etc. Each variable is subject to change with altitude.

The intensity of solar radiation on a horizontal surface is generally greater at higher altitudes. This results primarily because of the molecular effect of three attenuators of solar energy: air molecules, water vapor, and cloudiness. Cloudiness is by far the most important factor, except in cases of high levels of particulates, for example, volcanic eruptions. Although cloudiness tends to decrease with increasing altitude, some communities located at high altitudes with a peculiar meteorological or topographic setting may actually receive relatively small amounts of sunshine because of significant cloud cover.

In terms of loss of ultraviolet radiation to the atmosphere, one may consider total loss from the outer limits of the atmosphere to sea level as 100 percent. At 1,525 to 2,500 m (5,000 to 7,675 feet), only 80 percent of that loss will have occurred. Therefore, locations at altitudes of 1,500 to 2,500 m will receive some 20 percent more ultraviolet radiation than locations at sea level. Absorption of solar energy by water vapor strongly affects the longer wavelength infrared radiation but does not affect the ultraviolet radiation. Since water vapor concentrations generally decrease with increasing altitude, a site at 1,525 m will usually receive some five percent more total solar energy than a sea level locality.

From the central United States to the Rocky Mountains, land elevation generally increases, while atmospheric water vapor and cloudiness decrease. Consequently, Denver annually receives about 10 percent more solar radiation than St. Louis or Washington D.C., and about 20 percent more than Chicago. This difference, however, is due to different latitudes as well as to the higher altitude in Denver.

The normal variation of solar radiation with altitude may be influenced by air pollutants, while the intensity of solar radiation received at a given location

may affect the chemical behavior of these same pollutants.

Atmospheric pressure normally decreases approximately logarithmically with height. At an altitude of 1,458 m (4,781 feet), the pressure is approximately 850 mb (646 torr), a decrease of about 15 percent of the standard sea level value. The diurnal variation at a given altitude is normally on the order of one to three percent. It follows, of course, that comparable decreases in density occur with changes in altitude.

The average annual temperature depends to a considerable degree on the altitude of a location and its surrounding terrain. Higher altitudes generally have cooler summer temperatures, and winter temperatures can reach very low minima. Local terrain conditions have a marked influence on the cold season temperatures, frequently resulting in extreme temperature differences between stations at the same altitude. In all seasons, high altitude locations exhibit a large daily temperature range.

In the free troposphere, the wind speed normally increases with increasing height above sea level. However, the correlation between higher land elevations and higher wind speed is in part due to the occurrence of rugged terrain at higher altitudes. The dispersion of air pollutants is strongly dependent upon local wind conditions.

On the windward side of mountainous terrain, the amount of precipitation is considerably increased by the forced ascent of the air. The leeward slopes, on the other hand, are in the rain shadow and have much less precipitation.

The total precipitation also decreases on each range as one proceeds through a mountain system to the leeward side. For example, more precipitation occurs over the western than over the eastern Rocky Mountains. The amount of precipitation at any one location is, therefore, dependent in part upon its exposure and altitude. Because precipitation is one of the principal removal mechanisms for air pollutants, changes in altitude may contribute to significant pollution effects by this mechanism.

Chemical Properties and Phenomena

The photochemical reactions of pollutants to form smog are a function of several factors. The major ones are:

1. Concentration
2. Ultraviolet Radiation
3. Temperature

All three factors are vitally important to the kinetics of the reactions.

The rate of a photochemical reaction is represented by the general rate equation (1):

$$\text{Rate} = K[A]^m[B]^n \qquad (1)$$

where [A] and [B] represent reactant concentrations, m and n represent the stoichometry of the reaction, and K is the reaction rate constant. Therefore, a concentration increase results in a proportional effect on the rate of the reaction when m and n are unity.

At higher altitudes, the atmospheric pressure of the ambient air is lower than at low altitudes and this results in lower partial pressures of oxygen. Unless adjustments are made to increase air flow in engines, the lower oxygen content will result in higher emission rates of unreacted hydrocarbons from vehicular and industrial sources, the major source of photochemically reactive pollutants in urban areas.

Sunlight is necessary to initiate ambient photochemical reactions. The simplified, general mechanism for the formation of photochemical smog is given by the reactions:

$$NO_2 + h\nu \rightarrow NO + O \qquad (2)$$

$$O + O_2 \xrightarrow{M} O_3$$

$$O_3 + h\nu \rightarrow O_2 + O^* \qquad (3)$$

$$O^* + H_2O \rightarrow 2OH$$

$$OH + RH \rightarrow R + H_2O$$

$$R + O_2 \rightarrow RO_2$$

$$RO_2 + NO \rightarrow RO + NO_2$$

etc.

Solar radiation is supplied to these reactive pollutants not only by direct sunlight but also by reflection from the atmosphere and from the earth's surface. The quantity of light radiation supplied to the reactive pollutants is dependent on the solar spectral irradiance incident on the atmosphere, the solar zenith angle, the nature and amount of scattering, diffusion, absorption of radiance by the atmosphere, and the albedo of the surface under the region of interest. On the other hand, the proportion of radiation absorbed by the reactive pollutants is dependent upon absorption coefficients, concentration of pollutants, and effective path lengths. All of these factors must be considered when evaluating the effect of light on photochemical reactions. The mechanism of photochemical smog formation has been discussed by Demerjian *et al.*(1) and Moortgat and Warneck.(2) The exact reaction mechanisms proceeding from the primary step of light absorption are not completely understood. For the above reasons, it is difficult to make exact statements about the photochemistry of reactive pollutants even at sea level.

It is perhaps more convenient to limit the discussion to the effect of altitude on two properties: wavelength distribution and intensity. Altitude effects have been

observed for both of these properties. Most of the information available on these effects has been determined by use of aircraft at high elevations above a ground level reference point. Nader (3) reported a 14 percent increase in ultraviolet light intensity between Los Angeles (350 feet surface elevation) and nearby Mt. Wilson (5,700 feet surface elevation). These measurements were made on a relatively clear day. Included in the 14 percent was a 21 to 25 percent increase in light intensity of wavelength distribution between 3,050 and 3,450 Å, and a 12 to 15 percent increase in light intensity of wavelength distribution between 3,450 and 3,950 Å. These results would suggest that altitude significantly effects ultraviolet light intensity; however, a further evaluation of these results is necessary since pollution in Los Angeles may have been partly responsible for the observed difference.

If increasing altitude results in increases in the intensity of light at all wavelengths and the increase is greatest for the lower wavelength region, then the following effects will be expected:

1. Increased light intensity at higher altitudes will result and, therefore, there will be an increase in photochemical activity.
2. The rate of the primary step for the production of photochemical smog, NO_2 photolysis, will be significantly increased due to the increased intensity of shorter wavelengths of light at higher altitudes. The increased lower wavelength light may also have a great effect on reactions of other secondary pollutants such as the aldehydes and ketones.

Temperature is an important parameter in all chemical reactions. Temperature is a measure of the kinetic energy available to molecules; this energy directly affects the collision frequency between reactant molecules. Consequently, elevated temperatures produce higher collision frequencies between molecules resulting in a greater probability of a reaction occurring. Also, since most reactions have an activation energy, as the temperature increases, more energy is supplied to overcome this energy barrier, and the reaction rate increases.

Within the troposphere, ambient air temperatures generally decrease with increasing altitude, except in the case of temperature inversion. However, an industrialized city contributes a considerable amount of heat to its surrounding atmosphere. For this reason the ambient temperatures of the atmosphere above cities at higher altitudes may be higher than above adjacent non-urban locales. In general, however, the lower temperatures characteristic of higher altitudes should contribute to slowing of photochemical reactions.

To conclude, if emissions at high altitude are comparable to those found at lower altitudes, the greater solar intensity at high altitudes will tend to increase photochemical smog production, while the lower temperatures will tend to decrease it. Due to the different effects of these parameters and the complex interactions in photochemical reactions, it is not possible to provide a general prediction of the altitude effect on photochemical smog formation.

Effects of Altitude on Aerosol Dynamics[1]

The only mass transport parameters for air that exhibit significant dependence on elevation are air density (or molecular mean-free path) and temperature. It is possible that the rates of aerosol processes such as nucleation, condensation, dry and wet deposition, coagulation, and gas-to-aerosol conversion may be different at high elevation with respect to sea level. Also, the performance of aerosol instrumentation and the deposition efficiencies of aerosols may be a function of elevation.

The process of heterogeneous nucleation is not yet completely understood, and it is not possible to state whether nucleation rates for the same mass concentration of nucleating monomers would be increased or decreased at higher elevations; this rate also has a complex dependence on other factors, such as the aerosol size distribution in the air. The rate of condensation is not expected to be significantly different at high elevations since the half-life for molecular collisions with urban aerosols is on the order of one second. Coagulation rates of fine aerosols are pressure and temperature dependent; for the same temperature, fine aerosols should coagulate 20 to 40 percent faster at high elevations. A decrease in temperature decreases the coagulation rate.

The process of dry deposition for aerosols is not completely understood. Generally, the deposition of aerosols with diameters greater than 0.3 μm is discussed in terms of sedimentation and impaction. Settling for aerosols with diameters less than 75 μm at high elevations during cold periods (242°K) will be greater (10 to 20 percent) than at low elevations during warm (293°K) periods; however, there will be little difference when the temperatures are equal. Impaction efficiencies may be on the order of 20 percent greater at high elevation. Most likely, dry deposition velocities of coarse particles will be approximately equal for high

[1]For a more detailed discussion of this subject, see Appendix A.

and low elevations. Dry deposition of aerosols with diameters less than 0.3 μm is generally discussed in terms of Brownian diffusion. The fine aerosol deposition velocities will probably be about the same for high and low elevations at a temperature of 293° K; however, if the temperature is 242° K at the high elevation site, then the fine aerosol deposition rate will be lowered by about 20 percent.

The performance of aerosol samplers and monitors calibrated at lower elevations may be affected when used at high elevations. The devices that will be affected are those that size particles by the air resistance-to-motion principle. Such devices include sedimentation chambers, elutriators, impactors, cyclones, diffusion batteries, electrical mobility analyzers, etc. The most important parameter to be considered is the air viscosity for devices sizing aerosols with diameters greater than about 0.5 μm. The air viscosity is independent of pressure, but decreases as temperature decreases. Thus, elutriators, impactors, and cyclones are expected to increase in efficiency. The sizing of small particles by diffusion batteries depends on both the viscosity and the molecular mean-free path, and is handled in a direct manner by recalculating the aerosol diffusion coefficients. However, the electrical mobility analyzer performance is more complex due to its additional dependence on the level of aerosol charging.

One of the important differences in high and low elevations is the change in lung deposition efficiencies of aerosols. Since the air is equilibrated to body temperature before passing the pharynx, the air viscosity is constant in the lungs at high and low elevation. However, the pressure at high elevation is decreased, resulting in an increase in the molecular mean-free path. Thus, the particle diffusion coefficients will be increased. Coarse aerosols will have about the same deposition efficiencies in lungs at high and low elevations, but fine particles may be deposited with up to 20 percent greater efficiency at high elevation.

EFFECTS OF ALTITUDE ON SOIL

Soils at higher altitudes in the eastern United States are basically gray-brown podzolic soils. These are high in organic matter, have low acidity, and contain numerous microorganisms and earthworms. In the Rockies and the other mountains of the West, they vary from shallow soils of mountain, upland, and valley to the gray desert types.

Studies dealing with effects of pollutants on soils at high altitudes are limited in number. Therefore, it is necessary to theorize. At high altitudes, radiation and wind have easier access to the soil and rock surfaces due to less vegetation. Climatic changes are extremely important because of the precarious balance of the soil, its organisms, and the vegetation growing in the soil. Any pollutants which might bring about a change in soil acidity, to cause vegetational changes or influence mineral cycling, could adversely affect the soil. Nutrient cycling and the decomposition of leaf litter is of importance at surface elevations below the timberline, which includes almost all of the mountains of the eastern United States. Therefore, pollutant effects upon these processes can appropriately be studied in this area. Witkamp (4) has shown that bacterial and fungal populations generally are decreased at higher elevations. Temperature, particularly, plays an important role in the numbers of bacteria and fungi that are present and in the respiration rate of soil microorganisms.

Inman *et al.* (5) and Abeles *et al.* (6) have shown that soil microorganisms have the ability to take up CO and hydrocarbons from auto exhaust. Many other scientists have shown that hydrocarbons can be readily metabolized by microorganisms. However, very few studies have shown, at any altitude, how the changes in microbial populations in the soil influence the soil itself. There is a general need for soil studies at all altitudes.

The Inman *et al.* study indicates that CO uptake appears to be dependent upon altitude. The CO uptake decreases from about 80 μg/hr m^2 at sea level to approximately 5μg/hr m^2 at 610 m (2,000 feet). However, Inman points out that altitude is but one of several variables involved in the reactions. Other factors are temperature, soil type, and the types of microorganisms. These factors are difficult to separate. A study is required that uses the same soil with the same amount and types of microflora and microfauna. This soil could then be transported to different land elevations and the pollutant uptake measured. Inman's results show that the maximum CO uptake occurs at approximately 35° C. If higher land elevations have lower temperatures, then the CO uptake would be expected to decrease with all other variables remaining constant.

EFFECTS OF ALTITUDE ON WATER

For the purposes of this report, it is assumed that pollutant-to-water interactions take place mainly via the following mechanisms:

1. Pollutant contribution to the atmosphere from sea and land masses of water.

2. Pollutant removal from the atmosphere by scrubbing action of rain and by contact of the atmosphere with water masses.
3. Change of pollutant form due to chemical reaction with water.

Seiler and Junge (7) and Swinnerton *et al.* (8) have stated that the ocean and rain water are sources of carbon monoxide. Swinnerton found that rain water, collected at an altitude of about 1,525 m (5,000 feet), was supersaturated with carbon monoxide. As yet no mechanism has been proposed and verified to account for this phenomenon.

Organics with low boiling points that are immiscible with water [i.e., CH_2Cl_2, $(CH_3\text{-}CH_2)_2\text{-}O$] would evaporate rapidly into the atmosphere if discharged into a river, pond, or lake, and this would occur more rapidly at higher altitudes.

For this reason, pollutant control strategies for industrial activities operated at altitudes above approximately 1,525 m (5,000 feet) should consider the increased volatility of organic waste discharges to determine impact on the atmosphere.

With regard to 2 and 3 above, the scrubbing of pollutants from the atmosphere by water and the change of pollutant form due to reaction with water probably would not be significantly different between 1,525 m (5,000 feet) and sea level.

REFERENCES

1. Demerjian, K. L. , J. A. Kerr, and J. G. Calvert. The Mechanism of Photochemical Smog Formation. Adv. Environ. Sci. Technol. *4*:1-262, 1974.
2. Moortgat, G. K. and P. Warneck. Relative O('D) Quantum Yields in the Near UV Photolysis of Ozone at 298°K. Z. Naturforsch. Teil A *30*:835-844, 1975.
3. Nader, J. S., (ed.). Pilot Study of Ultraviolet Radiation in Los Angeles, October 1965. P.H.S. Publication No. 999-AP-38, U. S. Government Printing Office, 1967, pp. 1 - 98.
4. Witkamp, M. Microbial Populations of Leaf Litter in Relation to Environmental Conditions and Decomposition. Ecology *44*:370-376, 1963.
5. Inman, R. E., R. B. Ingersoll, and E. A. Levy. Soil: A Natural Sink for Carbon Monoxide. Science *172*:1229-1231, 1971.
6. Abeles, F. B., L. E. Craker, L. E. Florrence, and G. R. Leather. Fate of Air Pollutions: Removal of Ethylene, Sulfur Dioxide and Nitrogen Dioxide by Soil. Science *172*:914-916, .1971.
7. Seiler, W. and C. Junge. Carbon Monoxide in the Atmosphere. J. Geophys. Res. *75*:2217-2226, 1970.
8. Swinnerton, J. W., R. A. Lamontgne, and V. J. Linnenbom. Carbon Monoxide in Rain Water. Science *172*:943-944, 1971.

III. AIR POLLUTION MONITORING

INTRODUCTION

Gaseous air pollutants such as sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), etc., are measured by determining their concentrations in the ambient air. Since both these pollutants and the ambient air are gases, changes in pressure directly affect their volume. According to Boyles law, if the temperature of a gas is held constant, the volume occupied by the gas varies inversely with the pressure (as pressure increases, volume decreases). The major effect of altitude on air pollution monitoring is that volume differences result from the differences in pressure that prevail when monitoring is carried out at different land elevations. This pressure effect must be considered when measuring pollutant concentrations. Normal atmospheric pressure variations at any given sampling location have very little effect on air pollutant measurements. However, when comparing pollutant concentrations measured at significantly different altitudes, volume corrections are sometimes necessary depending on the pollutant concentration units used.

The two units most commonly used in reporting pollutant concentrations are micrograms per cubic meter ($\mu g/m^3$), a "mass of pollutant per volume of air sample" measurement, and parts per million (ppm), a "volume of pollutant per volume of air sample" measurement. When $\mu g/m^3$ units are used, volume corrections can be made such that results can be reported at a reference pressure (760 torr). When ppm units are used, volume corrections are not necessary because the ppm unit is not dependent on pressure effects.

The discussion on the following pages will show how altitude (pressure) variation effects should be considered when reporting air pollutant measurements expressed either as ppm or $\mu g/m^3$. Also a brief discussion is given on how altitude affects calibration and air monitoring instruments.

ALTITUDE EFFECTS ON CONCENTRATIONS MEASURED IN PPM

The measurement of gaseous air pollutants in ppm (volume per volume) units is widely used in the air pollution scientific community. The use of this unit has a number of advantages. It is dimensionless and is numerically equivalent to such ratios as microliters per liter, molecules per million molecules, and micromoles per mole. It is readily understood by non-scientific people and can be easily changed to "parts per billion" to eliminate decimal fractions.

The ppm unit is used primarily in reporting pollutant concentrations measured with continuous analyzers, because it is a ratio of two volumes and is therefore independent of pressure and temperature. Both gases (pollutant and air sample) closely follow the ideal gas law (Boyles law) where volume changes proportionately in response to changes in pressure; thus, their ratio remains unchanged. This means that an air pollution analyzer can measure concentrations in ppm under conditions of varying pressure without error due to the resulting changes in volume. This does not mean, however, that an analyzer can be calibrated at low altitude and then carried to a higher altitude without recalibration. In this case the sample air metering device would be affected by the pressure change from one altitude to another and recalibration would be necessary at the new altitude.

The primary disadvantage of the use of ppm units is the fact that while the ppm unit does not vary with pressure, the mass of a gaseous pollutant per unit volume does vary with pressure. For example, air containing 1 ppm of a pollutant at a high altitude such as Denver, Colorado, will still contain 1 ppm if that air is brought down to sea level. However, the mass per unit volume of air will increase with the decreasing altitude.

This relationship can be demonstrated as follows: recall that parts per million can be defined as microliters (μl) of gaseous pollutant per liter of air, or

$$\text{ppm} = \frac{\text{microliter } (\mu l) \text{ of gaseous pollutant (g.p.)}}{\text{liter (l) of air}} \quad (4)$$

If gas behavior is assumed to be ideal, the ppm concentration unit can be converted into moles of gaseous

pollutant per liter of air, a unit which is most useful in considering health effects caused by exposure to air pollution.

The derivation of moles of gaseous pollutant per liter of air from the ppm unit follows:

$$\frac{\text{moles of g.p.}}{\text{l of air}} = \text{ppm}\ \frac{\mu\text{l of g.p.}}{\text{l of air}} \times$$

$$\frac{\text{1 mole of g.p.}}{\text{24.45 l of g.p.}} \times \frac{P}{760} \times \frac{298}{T} \times \frac{10^{-6}\text{ l of g.p.}}{\mu\text{l of g.p.}} \quad (5)$$

where P = atmospheric pressure at sampling site, torr,

T = temperature at sampling site, °K

760 = standard pressure, torr,

298 = reference temperature, °K (298° K or 25° C is used by EPA as more appropriate to ambient air measurement conditions than the conventional 273° K or 0° C), and

24.45 = liters of gas/mole, at standard pressure and reference temperature

g.p. = gaseous pollutants

which simplifies to:

$$\frac{\text{moles of g.p.}}{\text{l of air}} = \text{ppm} \times 1.604 \times 10^{-9} \times \frac{P}{T} \quad (6)$$

It is evident from equation 6 that constant parts per million contain differing numbers of moles per unit volume of air as pressure (and temperature) changes. For this reason exposure to identical parts per million concentration at differing pressures does not expose the receptor to identical numbers of moles of pollutant per unit volume of air. Although air pollutant concentrations reported in ppm units are not directly affected by altitude differences, the effective mass per unit volume differences should be considered when interpreting data taken from different altitudes. It is important to note that if concentration results, in ppm, are to be converted to moles per liter air or to $\mu g/m^3$, the pressure at which the sample was taken must be known.

ALTITUDE EFFECTS ON CONCENTRATIONS REPORTED IN $\mu g/m^3$

The micrograms per cubic meter unit is used primarily for pollutants which are not gases. However, it is also used for gaseous pollutants when the measurement methodology is based on a manual method (i.e., the pararosaniline method for measuring SO_2). In the latter case, samples are generally collected in liquid absorbing solutions which are taken to a central laboratory for chemical analysis. In this case, the pollutant is analyzed on a weight basis and, consequently, results are computed in $\mu g/m^3$ units, which can be converted to ppm units if the pressure and temperature at which the sample was taken are known.

When air pollutant concentrations are reported in $\mu g/m^3$, the volume of air sampled must be corrected to a reference pressure and temperature (temperature effects are not considered in this discussion) if the comparisons of data from different locations are to be made. If not, the calculation of the mass of a pollutant per unit volume of air sampled will be a function of pressure, and concentrations obtained will vary with the altitude of the sampling site.

For example, consider a situation in which 50 $\mu g/m^3$ of particulate matter is measured without correction at a location having an atmospheric pressure of 625 torr (common in Denver). If a cubic meter of that air is pressurized to 760 torr (reference conditions), it would be compressed to about 80 percent of its original volume, and the correct particulate concentration per cubic meter would be correspondingly higher, as the following calculation shows:

$$V_2 = \frac{P_1 V_1}{P_2}$$

where V_2 = volume at reference conditions,

P_2 = 760 torr,

V_1 = 1 m^3,

P_1 = 625 torr, and

therefore,

$$V_2 = \frac{625\text{ torr} \times 1\ m^3}{760\text{ torr}} = 0.82\ m^3;$$

thus, the particulate matter concentration would be

$$\frac{50\ \mu g}{0.82\ m^3} = 61\ \mu g/m^3.$$

It is obvious that volume corrections should be made when pollutant concentrations, in terms of $\mu g/m^3$, are compared between locations of different altitudes. For purposes of comparison, all measurements reported in $\mu g/m^3$ should be corrected

to the reference pressure of 760 torr, as specified in the Code of Federal Regulation, Part 50.3 (40 CFR Part 50.3).

It should be noted here that historically the EPA National Air Surveillance Network (NASN) has made no corrections for the differing atmospheric pressures at the various sites in its network. These corrections would require measurement, or estimation, of the barometric pressure during sampling at each site. Pragmatically, for many sites, the elevation correction would be comparable to or less than the intrinsic variability of the earlier monitoring methods.

ALTITUDE EFFECTS ON CALIBRATION

Dynamic calibration of methods and instruments for measuring gaseous air pollutants is commonly done in one of two ways. The first of these employs a known amount of a pollutant gas, generated at the altitude of measurement and diluted with pollutant-free air to the various concentrations needed for calibration. Permeation tubes and constant flow ozone generators are two examples of devices using this procedure to prepare calibration gases. The second calibration method uses known mixtures of the gaseous pollutant in a diluent gas, contained in pressurized cylinders. These cylinders are transported to the site of the measurement needed for calibration. Altitude does not generally affect either of these procedures. When permeation tubes (or an ozone generator) are used, the calibration gas is prepared at the altitude where it is being used. When pressurized cylinders are used, the concentration of pollutant in the cylinder is assayed in ppm units, which is independent of pressure.

When working in units of $\mu g/m^3$ (mass per volume), a correction must be applied in those calibration procedures using calibration gases that have been prepared at one altitude and used at a different altitude. For example, a cubic meter of a calibration gas that contains 100 μg of a pollutant at sea level atmospheric pressure will expand with the decreasing pressures at higher altitudes. Thus, a cubic meter of the expanded gas is left with proportionately less of the 100 μg of pollutant.

ALTITUDE EFFECTS ON AUTOMATED METHODS (ANALYZERS)

Most air pollution analyzers can be operated at almost any surface elevation in the continental United States. The exceptions are the monitoring systems that employ hydrogen flames, such as the flame ionization detector for hydrocarbons or the flame photometric detector for SO_2. At altitudes in excess of 3,000 m (10,000 feet), the partial pressure of oxygen is sufficiently low that an auxiliary oxygen supply may be necessary to support the combustion of these flames.

As stated above, the main influence of altitude on measurements is that of pressure, which alters the mass of a pollutant per unit volume. For example, 1 ppm of NO_2 measured at 25°C and 760 torr pressure is equivalent to 1,880 μg of NO_2 per cubic meter of air; whereas, 1 ppm of NO_2 measured at 25°C and 625 torr pressure is equivalent to 1,546 μg of NO_2 per cubic meter of air. Since most commercial air monitoring instruments record data in ppm, a knowledge of the prevailing atmospheric pressure and temperature is needed in order to convert correctly ppm readings to $\mu g/m^3$ at the condition of measurement. It should be noted that factors given with the EPA reference methods for measuring the criteria pollutants have been defined such that any properly measured ppm concentration can be converted correctly to $\mu g/m^3$, under the reference conditions of 760 torr and 25°C.

IV. STATIONARY SOURCES

EMISSIONS

There has been no documented evidence to date on any altitudinal effect on the nature, quantity, or characteristics of emissions from stationary sources. Based upon current knowledge, one would not expect to see measurable differences due to altitude, except, perhaps, with losses by evaporation from dry cleaning plants (organic solvents), petroleum products (volatile matter), and surface-coating operations. Altitude effects on evaporation loss from storage can be expected to be minimal.

In the case of particulate matter, two competing factors can be expected to affect the nature and quantity of atmospheric particles. The two factors are less complete combustion processes caused by the lower atmospheric pressure (less available oxygen) and the lower air viscosity. The first factor would be expected to result in more (numerically) and larger particles; the second factor would be expected to cause more rapid fallout of particles, thus resulting in a smaller mean mass diameter. Initial ambient air measurements at high altitudes have shown the mean mass diameter to be slightly larger than anticipated.

MEASUREMENTS

One must consider the two general types of measurement systems separately. In the case of optical (non-contact) methods using a fixed path length, the lower atmospheric pressure at high altitudes means fewer molecules are in the optical path to absorb the light energy. This factor would be compensated for in the calibration method. In the instance of manual sampling systems, pressure may affect the gas solubilities in collection media. However, variations due to this effect are not expected to affect reproducibility of the measurement method. No other measurements are likely to be affected by slight changes in pressure.

Pitot tube velocity measurements should be affected by pressure differences due to altitude. The measurements are directly proportional to the density of the gas, and the primary effect of increased altitude is a smaller pressure change for a given change in air stream velocity. In the Denver area, this would result in a sensitivity decrease of approximately 15 percent, but the decrease could be greater at very low velocities.

Since the measurement systems for particles use isokinetic sampling techniques and all measurements are referenced back to standard atmospheric pressure and temperature, no altitudinal effect is expected.

CONTROL TECHNOLOGY FOR STATIONARY SOURCES

For essentially all combustion devices, the mass air required to produce a given amount of heat release is essentially constant. Because of the reduction in atmospheric pressure with increasing altitude, the volume of air and exhaust gas per unit of energy will increase proportionately. Thus, most atmospheric pressure handling equipment must be sized 7 to 15 percent larger at 1,525 m (5,000 feet) land elevation than at sea level and will cost 5 to 10 percent more. Such gas handling equipment includes, for example, scrubbers, baghouses, catalytic reactors, fans, and compressors. The effect of atmospheric pressure is insignificant compared to variations that would occur at any altitude in pollutant concentration, gas temperature, air dilution rates, and other source parameters.

V. MOBILE SOURCES

INTRODUCTION

This section briefly describes the effect of changes in altitude on regulated emissions from motor vehicles. Regulated emissions are those for which emission standards apply; these include HC, CO, NO_x, and particulate. Both exhaust engine emissions and evaporative emissions are discussed.

The references included at the end of this section represent a selected few to provide an introduction to the very substantial literature on the general subject. No attempt has been made to cover all aspects.

THEORY

The engine combustion process is affected when the engine is forced to operate at differing altitudes. Increase in altitude results in a decrease in atmospheric pressure accompanied by a decrease in air density. These density changes alter the mass of air available for the combustion process. Consequently, changes in altitude create changes in the air-fuel ratio at which the engine must operate. Because combustion efficiency and exhaust emissions are a function of air-fuel ratio, altitude changes, unless compensated or corrected for, affect both engine performance and emissions. For this reason, vehicles are often "retuned" when they are to be operated at higher altitudes.

Carbureted engines, which are essentially volumetric devices, are those most susceptible to altitude change. Since the fuel flow under fixed engine operating conditions is only slightly affected by pressure changes, the decreasing density of the inducted air at increased altitude results in engine operation with richer mixtures.

For a carburetor installation undergoing an altitude change from sea level to 1,525 m (5,000 feet), the result would be approximately seven percent enrichment of air-fuel ratio. (1) This would result in decreased power, decreased engine efficiency, and decreased NO_x emissions, and increased HC and CO emissions. However, proper adjustment of the ignition timing for vehicles to be operated at high altitudes would reduce the magnitude of these effects.

Fuel injected engines behave somewhat differently when subjected to changes in altitude. Although some injection systems have been designed to compensate for altitude effects, numerous noncompensating systems are in use which cause a leaning of the air-fuel ratio with increasing altitude. These systems commonly utilize speed-density control systems without back pressure sensing. It has been reported that a change from sea level to 1,525 m (5,000 feet) of altitude would result in a 2.1 percent leaning of the air-fuel ratio of the mixture for noncompensating injection systems.(1) This leaning would generally tend to reduce engine regulated emissions slightly.

The theoretical effect of altitude changes on evaporative emissions should also be considered. Evaporative emissions are caused primarily by the venting of fuel vapors from the carburetor float chamber and vehicle fuel tank. These can constitute a sizable source of HC emissions in the absence of appropriately functioning control devices.

Low barometric pressures prevalent at high altitudes effectively lower the distillation temperature curve of gasoline causing it to become more volatile at all temperatures. Gasoline losses increase significantly, especially during vehicle hot-soak when temperatures are elevated following engine shutdown.(2)

Diurnal evaporative losses show a strong correlation with gasoline Reid Vapor Pressure, which for high-altitude fuels, is generally lower than for low-altitude fuels.(2-4) Although this fact would imply that the altitude effect on volatility might be compensated for, in actuality, high altitude evaporative losses are greater according to surveillance test data obtained in the Los Angeles and Denver areas.(5)

Many additional factors such as an altitude-temperature relationship, fuel characteristics, fuel distribution efficiency, injection spray geometry (diesel), fuel-air mixing efficiencies, etc., have a

bearing on engine performance and emissions at high altitudes. In the case of diesel engines, a fixed fuel injection rate can be maintained over only a moderate range of altitudes if excessive smoke and deposits are to be avoided.

MEASUREMENTS

All differences in recommended measurement procedures at high altitudes are practical and not theoretical. All certification measurements are corrected volumetrically to a mass basis at standard sea level temperature and pressure.(6) All measurements of physical and/or chemical moieties must be corrected to a common physical base if the results are to have any comparability. The base *must* include an altitude correction if it is a relevant parameter.

All affected measurements currently specified in the Federal Register include an altitude (i.e., barometric pressure) correction. Any measurement that does not include this parameter should be considered suspect unless made at sea level and at 25°C.

EMISSIONS

As theory has predicted, regulated exhaust emissions from mobile sources are quantitatively affected by altitude. Changes in air-fuel ratio brought about by operation at varying altitudes are largely responsible for variation in emission rates. When these emissions are expressed as ppm, data regarding carbureted vehicles, which comprise the bulk of mobile source emitters currently in the United States, are most susceptible to altitude effects. Those vehicles that are not specifically designed for high altitude operation will emit more hydrocarbons and carbon monoxide and less nitrogen oxides with increases in altitude. Smoke emitters, such as diesel engines, will emit greater quantities of visible, carbonaceous material with increasing altitude. The smoke capacity of a turbocharged diesel engine almost triples between 183 and 1,830 m (600 and 6,000 feet) and then falls off at higher altitudes. The same is true of smoke from diesel locomotives.(7,8)

Only limited information is available on the functional relationship between emissions and altitude. From the information which is available, it has been determined that a near linear relationship exists between HC, CO, and NO_x emissions and altitude. A research paper published by Volkswagen (9) contains data on a single vehicle which was tested at six different altitudes. The linear regressions obtained using these data are expressed as:

$$\text{HC}: \quad E = 2.95 + 0.00072\,A$$

$$\text{CO}: \quad E = 30.33 + 0.0074\,A$$

$$NO_x: \quad E = 2.82 - 0.00027\,A$$

where E is the emission in grams per kilometer and A is the altitude in meters. The rates, expressed as a percent change per 100 m, are 2.5, 5.0, and -2.0 percent for HC, CO, and NO_x, respectively. Because of the linear relationship cited above, interpolation may be used to determine an emission rate at a given altitude when emission rates at both a high and low altitude are known. For such a case, the following expression may be used:

$$EF_u = EF_l + \frac{EF_h - EF_l}{(A_h - A_l)} (A_u - A_l)$$

where EF_u = user emission factor,
EF_l = low altitude emission factor,
EF_h = high altitude emission factor,
A_u = user altitude,
A_l = low altitude level, and
A_h = high altitude level.

This expression can be readily applied to emission factor data listed for both high and low altitudes. The average low altitude is assumed to be about 150 m (500 feet) and 1,677 m (5,500 feet) for the average high altitude.(10)

Evaporative emissions from gasoline powered vehicles are categorized as either hot-soak losses or diurnal losses. The hot-soak losses occur during the vehicle's cooling-down period immediately following engine shutdown. Diurnal losses occur while the vehicle is not operating and is essentially in temperature equilibrium with the environment.

In an emission surveillance study conducted on in-use 1976 model vehicles, data were obtained on evaporative emissions in both the Los Angeles and Denver areas. The former city represents the sea level case, while the latter represents the high altitude case at about 1,585 m (5,200 feet). Both hot-soak and diurnal evaporative losses were determined for 20 different vehicles using the Sealed Housing for Evaporative Determinations (SHED) technique. In both cases Denver vehicles were found to have significantly higher evaporative emissions. The mean diurnal loss in Denver was 21.7 g as compared with 7.8 g in Los Angeles, and the mean hot-soak loss in Denver was 10.5 g versus 5.4 g in Los Angeles. Assuming an average of 3.3 trips per day and 47.3 km (29.4 miles)

per day, the combined evaporative emission losses are 1.2 g per km (1.9 g per mile) in Denver versus 0.56 g per km (0.9 g per mile) in Los Angeles.(5)

CONTROL DEVICES

Control of air-fuel ratio is the key to any system which is designed to compensate for altitude differences in mobile source emissions. Carburetors have been designed with aneroid pressure sensors to correct for altitude effects. The sensor utilizes feedback to control the amount of inlet air which will bypass the carburetor's venturi. Although carburetors of this type have been on display, none are currently being used to any extent by the major automobile manufacturers.

The three-way catalyst systems which are in production utilize the feedback from an oxygen sensor located in the exhaust gas stream to control air-fuel ratio. This is possible because exhaust oxygen level can be directly related to the engine operating air-fuel ratio. The system is designed to control air-fuel ratios within an extremely narrow range in order to achieve 80 percent catalyst efficiency. Control is within the range of 0.02 to 0.08 units of air-fuel ratio for most installations.(11) Foreign companies employing three-way catalysts on their vehicles have used the feedback system in conjunction with fuel injection systems. Domestic companies, on the other hand, have recently certified three-way catalyst vehicles that have carbureted systems. The only shortcoming that the three-way catalyst systems possess with regard to high altitude operation is the limited range of response designed into the system itself.

Some fuel injection techniques are sophisticated to the point that control of air-fuel ratio is possible over a wide range of altitudes. Engines having speed-density control systems with back-pressure sensors essentially can compensate for altitude changes. Another fuel injection approach has been to monitor the mass flow of air into the engine by using volumetric flowmeters with pressure and temperature sensors. A microprocessor with flowmeter and sensor inputs is used to calculate the air flow, and the fuel is metered accordingly.

REFERENCES

1. Bolt, J. A., S. P. Bergin, and F. J. Vesper. The Influence of the Exhaust Back Pressure of a Piston Engine on Air Consumption Performance, and Emissions. SAE Prepr. (730195), 1973.
2. Wade, D. T. Factors Influencing Vehicle Evaporative Emissions. SAE Trans. *76*:811-823, 1968.
3. Biller W. E., M. Manoff, J. Sachdev, W. C. Zegel, and D. T. Wade. Mathematical Expressions Relating Evaporative Emissions from Motor Vehicles Without Evaporative Loss Control. SAE Prepr. (720700), 1972.
4. U.S. Department of the Interior, Bureau of Mines. Motor Gasolines, Summer 1974. Petroleum Survey No. 88, 1975.
5. Rutherford, J. A. Automobile Exhaust Emission Surveillance--Analysis of the FY 1975 Program, EPA-560/3-77-022, USEPA, Ann Arbor, Mich., 1977.
6. Control of Air Pollution from New Motor Vehicles and New Motor Vehicle Engines. Fed. Regist. *36*:128, pp. 12652-12664.
7. Ephraim, M. Jr. Status Report on Locomotives as Sources of Air Pollution. Internatl. Conf. on Transportation and the Environment, Part I. SAE, New York, 1972, pp. 9-13.
8. Dennis, J. W. Turbocharged Diesel Engine Performance at Altitudes. SAE Prepr. (710822), 1971.
9. Schurmarn, D. and H. Klingenberg. Considerations on a Measuring Program to Investigate the Influence of the Ambient Air Conditioning on Vehicle Exhaust Emissions. Research Report No. MT-F5-77/13, Volkswagenwerk, A6, 1977.
10. Compilation of Air Pollution Emission Factors. Third Edition, AP-42, USEPA, Research Triangle Park, N.C., 1977, pp. 3.1.1.-1 to 3.3.3.-2.
11. Sittig, M. Automotive Pollution Control Catalysts and Devices. Noyes Data Corporation, Park Ridge, New Jersey, 1977, pp. 195-214.

VI. AIR POLLUTION EFFECTS

HUMAN HEALTH

General Considerations

Alterations of drug and toxic effects in man at high altitudes may be anticipated because of significant physiological alterations occurring at altitudes greater than 2,290 m (7,500 feet). These physiological alterations and most overt symptoms, including the syndrome of mountain sickness, result almost entirely from anoxia due to the diminishing oxygen content of the rarified atmosphere.

In addition, significantly lowered total atmospheric pressure can result in higher concentrations of toxic gases or fumes when the emission occurs in enclosed spaces.

For these reasons, and especially since the advent of the Space Age, a wealth of information on the effect of hypobaric environments on drug and toxic actions might be presumed to exist. In fact, the opposite is true.

A literature search of more than 500,000 publications in relevant subject areas uncovered very few publications dealing directly with the differential effects on human health caused by exposure to air pollutants at high altitudes. This statement does not include work on carbon monoxide, which will be treated separately in this report. Nor does it include high altitude problems of gas/vapor anesthetics which are well understood and predictable. There is a reduction of potency and duration of actions due to lowered partial pressure in all but completely closed systems. It may be that implications from these kinds of observations account for the lack of experimental interest in the influence of hypobaric environments on the effects of other volatile noxious agents or particulate pollutants. Experts in oxygen-related physiology or aero-toxicants generally agree that there is a great lack of knowledge in this area of pharmacology and toxicology.

Hypobaric Pharmacology-Toxicology

Despite the shortage of information, it is possible to make some predictions based on pharmacological principles, gas physics, and well-documented physiological obeservations on man's response and adaptation to high altitudes.

If it is true that no significant physiological alterations occur much below 2,290 m (7,500 feet), it is obvious that the following discussion will apply only to a very small fraction of the American population. Perhaps that is the reason why, with the exception of teaching the principles of anesthetics, the medical schools at Denver and Salt Lake City teach pharmacology and toxicology much the same as elsewhere.

In unenclosed spaces in free equilibrium with the atmosphere, partial pressures of gaseous pollutants decrease with increasing altitude. This results in decreased alveolar partial pressure which reduces systemic absorption. There probably is little altitudinal effect on local injury potential. Responses to particulate pollutants would not be affected by the lower atmospheric density.

In enclosed spaces at high altitudes, a given quantity of pollutant initially will reach a higher concentraion in higher partial pressure relative to oxygen than is reached at sea level; however, the absolute alveolar partial pressure may or may not be increased. Absorption as well as local injury potential may be increased.

Significant alterations in alveolar ventilation occur at high altitudes. There is an invariable increase in this parameter, the maximum of which is a function of the particular altitude. This maximum is reached within 100 hours for new arrivals at high altitudes. Prolonged stay at these levels results in very gradual decline (over years), but even natives have a higher ventilation rate at rest. This results in higher aero-toxicant dosage, especially for particulates and gaseous pollutants produced in enclosed spaces.

Effects of altitude on absorption of aero-toxicants can be summarized as follows:

1. Increased blood flow seen most prominently after acute introduction to high altitude and also in the early stages of adaptation will

promote increased absorption of soluble aero-toxicants.

2. Increased alveolar diffusing capacity in natives and adapted sojourners will have similar effects.
3. Reduced partial pressures of gaseous pollutants will decrease absorption.

Effects of high altitude on physiological fate of absorbed toxicants include the following:

1. Due to increased blood flow, there will be increased absorption by peripheral tissues of aero-toxicants initially absorbed by the lungs.
2. The decreased plasma volumes cause increased plasma concentration of dissolved toxicants which will also increase absorption by peripheral tissues.
3. Reduced pressure gradients across membranes will decrease translocation.
4. A redistribution of blood flow away from the skin occurs at high altitude, an effect which may favor translocation of toxicants to vital organs.

While no specific information is available on altitudinal alterations in metabolism of aero-toxicants, Merritt and Medina (1) showed that hexobarbital sleeping time decreased in mice which had been acclimatized to a hypobaric atmosphere. A similar decrease was shown for zoxazolamine paralysis time. In both instances increased hepatic microsomal enzyme activity could be demonstrated, resulting in more rapid declines of blood levels of these drugs.

No definite trends can be deduced from sketchy discussions in the literature. (1-6) When renal blood flow decreases, there appears to be an increased filtration rate. A tendency towards dehydration at high altitudes implies that excretion is diminished and blood and tissue levels of soluble toxicants or active metabolites are prolonged.

An interesting example, experimentally investigated, is the tenfold increase of amphetamine toxicity in mice and rats under hypobaric conditions (acute and acclimatized). This was found to be due to increased brain levels of catecholamines.

Other examples of hypobaric effects cited by Medina and Merritt (6), are increased toxicity of digitalis in cats, of strychnine in rats and of reserpine in mice.

Effects of Carbon Monoxide Under Hypobaric Conditions[2]

The effects of CO exposure and of hypoxia induced by high altitudes are similar. Much experimental data suggest that when high altitudes and CO exposures are combined, the effects are additive. *In vivo,* there is an interaction between the two factors such that exposure to one may induce a physiological response that influences the response of the body to the other. For example, Forbes *et al.* (7) have shown that during light activity their subjects had an increased rate of CO uptake at an altitude of 4,880 m (16,000 feet) compared to that at sea level, becasue of the hyperventilation that results from the decreased partial pressure of oxygen (P_{O_2}). When the ventilation rate was corrected to its value at sea level, the rate of uptake of CO decreased to a value within 10 percent of the sea level value.

Although the effects of hypoxia and CO appear to be additive at very high altitudes, individually they produce different physiological responses. This is because they have different effects on blood P_{O_2}, on the affinity of O_2 for blood hemoglobin, on the extent of oxyhemoglobin (O_2Hb) saturation, and on ventilation. The presence of carboxyhemoglobin (COHb) increases the affinity of the remaining hemoglobin for O_2, but lowers the total O_2Hb satuaration. The ventilation rate appears to be influenced by receptors in the carotid and aortic bodies that are responsive to blood P_{O_2}, and P_{CO_2}. (8) Hypoxia results in a lowering of the P_{O_2} and increased ventilation ensues; in CO exposure, the P_{O_2} apparently does not change sufficiently to induce increased ventilation.

Several different physiological and psychomotor tests have been used to determine the effects of altitude with and without CO. Pitts *et al.* (9) have observed the physiological responses to exercise when blood COHb levels were increased by 6 percent and 13 percent in a group of 10 men at simulated altitudes: 0; 2,130; 3,050; and 4,575 m (sea level; 7,000; 10,000; and 15,000 feet). The parameters measured were pulse rate, respiratory rate, and minute ventilation. A previous study had indicated that in subjects at rest, the pulse showed no change with atmospheric pressure down to that corresponding to an altitude of 5,000 m (16,500 feet). After regulated exercise at atmospheric pressures corresponding to altitudes from sea level up to 6,360 m (21,000 feet), however, it showed a steep, almost linear increase. Of the parameters measured in both these studies, mean pulse rate during exercise and for the five minutes immediately following exercise showed the closest correlation with blood COHb and ambient P_{O_2}. At sea level, an increase of 13 percent in COHb increased the mean exercise pulse rate from 105 to 112 and the recovery pulse rate from 91 to 98. An increase

[2]For a more detailed discussion of this subject, see Appendix B.

of six percent COHb produced a significantly higher exercise pulse rate compared to that produced by simulated increase in altitude alone. Pitts calculated that for every one percent increase in blood COHb in normal subjects, up to 13 percent COHb, the increase in exercise pulse rate is equal to that which would be produced by a 100-m (335-foot) rise in altitude throughout the range of 2,130 to 3,050 m (7,000 to 10,000 feet). It is likely that some of the subjects were smokers, since the group mean control COHb level ranged from 2.88 to 3.64 percent on different days. Since the smokers would have been preconditioned in part to the effects of CO, their responses to additional small quantities of CO might be expected to be lower than those of nonsmokers. This could have masked the additive effect of CO and hypoxia. A more recent study indicated that cigarette smokers may be partially adapted to carbon monoxide. (10)

Another study compared the effects of CO exposure and altitude. (11) Eight healthy male subjects were divided randomly into two groups of four each; each group followed a different daily schedule. The subjects were briefly exposed daily for 10 days to concentrations of five percent CO (57,500 mg/m^3 or 50,000 ppm) at four-hour intervals between the hours of 7 a.m. and 11 p.m. The doses were sufficient to give an average COHb level of 15 percent, although values ranging between 5 and 25 percent were recorded. A variety of circulatory, ventilatory, and renal function tests were performed during the course of the experiment. The same experimental protocol was carried out on the same eight subjects after they spent 10 days at a simulated altitude of 3,430 m (11,225 feet). This condition gave roughly a degree of hypoxemia equilalent to that given by 15 percent COHb. The data obtained from the two studies are compared in Table 1. Of great significance are the circulatory and ventilatory responses to the two types of hypoxic conditions. As expected, CO hypoxemia shifted the O_2Hb dissociation curve to the left; whereas, high altitude caused a shift to the right, the latter occurring during the first 24 hours. At increased simulated altitude, both the cardiac output and the ventilatory rate increased with the first 24 hours; whereas, CO had no consistent effect on these parameters.

The lowered arterial P_{O_2} at simulated high altitude most likely stimulated the chemoreceptors in the aortic and carotid bodies, with the resultant regulatory changes in ventilation. Mills and Edwards (12) have shown that these chemoreceptors are also stimulated during CO inhalation. These investigators have suggested that the lack of ventilatory response during CO hypoxemia is a result of depression of respiratory centers in the central nervous system. The effects of the two types of hypoxemia at the cellular level can be estimated by comparing the P_{O_2} of the mixed venous blood under both circumstances, since this reflects tissue P_{O_2}. The data in Table 1 show that the average P_{O_2} of mixed venous blood in CO hypoxemia is lower than in hypoxic (high altitude) hypoxemia. In both types of hypoxemia, a lowered tissue P_{O_2} is expected; as indicated by the mixed venous P_{O_2}, this was more pronounced in CO hypoxemia under the conditions observed. At increased simulated altitude, the shift of the O_2Hb curve to the right and the circulatory and ventilatory responses compensate for most of the associated tissue hypoxia during the first 24 hours. Such regulatory mechanisms do not appear to be stimulated by CO hypoxemia, and hence, CO hypoxemia may be considered to be more of a physiological burden than comparable levels of hypoxia hypoxemia.

In a study released by the National Asthma Center, the effects of low-level carbon monoxide exposure at 1,610 m (5,300 feet) for healthy young men was reported. (13) For COHb levels ranging from 0.96 to 1.15 percent, the effects of CO on exercise performance are similar to, but not greater than, effects at sea level.

Other studies on the combined effects of CO and altitude have used psychomotor tests. Variable results have been reported, but some of these may be explained by the use of different tests and others by the lack of proper controls. The flicker fusion frequency (FFF) and the critical flicker fusion (CFF), often employed in these studies, have recently been criticized because of their lack of reliability. (14)

McFarland *et al.* (15) have used the increased threshold of visual perception as an index of the effect of both CO and high altitude. It is pertinent to note at this point that McFarland *et al.* found that visual perception was impaired in a single subject who had a COHb level of about five percent at sea level. This is equivalent to the impairment associated with low P_{O_2} at an altitude of 2,130 m (7,000 feet).

In another experiment, a group of four trained subjects was used to study the time course of recovery from CO and altitude. (16) Data from a single subject suggest that it takes longer to recover from a given COHb level than from an equivalent lowering of P_{O_2} due to altitude. The difference could not be accounted for wholly by the presence of COHb. It is possible that the compensatory mechanisms normally activated by lowered P_{O_2} were not activated when CO caused the drop in O_2Hb saturation. Alternatively, it is also possible that CO exerts a specific toxic effect on the

TABLE 1. AVERAGE DATA FOR EIGHT SUBJECTS (DIVIDED INTO TWO GROUPS OF FOUR) TO COMPARE EFFECTS OF CO AND SIMULATED HIGH ALTITUDES ON VARIOUS PHYSIOLOGICAL PARAMETERS (11)

Test	Effect of 15% COHb	Effect of 3,420 m simulated altitude
O_2Hb saturation curve	Shift to left	Shift to right
Affinity of Hb for O_2	Increased (within 12 hr)	Decreased (within 24 hr)
Mixed venous oxygen tension, by estimation	10 to 20% decrease throughout exposure period	20% increase on first day, 10% decrease on second day, return to normal for rest of experimental period
Ventilation		
V_ESTPD[a] - rest	No change	15 to 20% decrease
- work	Slight increase on first day	Slight decrease
V_EBTPS[b] - rest	No change	30% increase
- work	No systematic change	35% increase on first day; 50% increase by tenth day
Respiratory rate - rest	No change	15 to 35% increase
- work	No change	15 to 35% increase
Circulation		
P_{ACO_2}[c] - rest	Almost unchanged	Continuous decrease from 90 to 75% of control
$P_{\bar{v}CO_2}$[d] - rest	Almost unchanged	Continuous decrease from 90 to 75% of control
Cardiac output	Group 1 increased 27% on first day, followed by return to normal; no change in Group 2	Group 1 increased 35 to 45% for the entire 10-day period Group 2 increased 25% by fourth day and returned to normal by end of stay
Mixed venous-arterial		
CO_2 difference, by day;	Group 2 showed no change	Group 1 decreased 15 to 20% for the entire 10-day period; Group 2 decreased on fourth day only
- work	Group 1 increased 20% on third and fifth days; no other changes noted	15 to 25% increase for the entire 10-day period
Renal function		
Glomerular filtration	50% increase on first day, return to normal on second day, remain within 20% of control for rest of experimental period.	Very slight decrease but close to control value
Renal plasma flow	40% increase on first day, return close to pre-exposure value on second day, remain < 15% below control value for rest of experimental period	Very slight decrease, but close to control value
Diuresis	Increase of 400 to 500 ml	Increase to more than twice control by sixth day
Serum lipids (cholesterol)	No significant change for first 4 days; 6% increase in last 2 days ($p<0.05$)	6 to 9% increase in first 2 days
Hematocrit	No change	Very slight increase (43.5 to 47)
Reticulocyte count	Threefold increase on third day; nearly fourfold increase by sixth day	Twofold increase on third day; nearly threefold by ninth day

[a] V_ESTPD (l/min) - ventilation at 0°C, 760 torr, dry.
[b] V_EBTPS (l/min) - ventilation at body temperature and ambient pressure saturated with water vapor.
[c] P_{ACO_2} - alveolar carbon dioxide tension.
[d] $P_{\bar{v}CO_2}$ - mixed venous carbon dioxide tension.

central nervous system that is unrelated to the COHb level.

In both studies just described, the investigators imply that the subjects exhibited similar responses, but they do not supply supporting data. Other investigators have commented on the great variability in response between subjects when similar tests have been used.

Lilienthal *et al.* (17) produced an impairment in FFF in five subjects at simulated altitudes of 3,050 to 3,650 m (10,000 to 12,000 feet). Exposure to CO (COHb increases of five to nine percent) combined with decreased atmospheric pressure equivalent to an altitude of 1,525 to 1,830 m (5,000 to 6,000 feet) effected an impairment in FFF, although neither of these stresses alone affected the FFF. The data indicate that an increase in the COHb level of 8 to 10 percent above resting values caused the tolerance for altitude altitude to be lowered by 1,220 m (4,000 feet) or more.

It should be noted that impairment in FFF is not necessarily consistent with a given COHb percentage. For example, at simulated pressure equivalent to 1,525 m (5,000 feet), one subject showed a depressed FFF at 8.7 percent COHb; yet , in another experiment at the same pressure, his FFF remained constant at 10.5 percent COHb. There is a possibility that COHb determinations in this experiment were inaccurate. The subjects' resting COHb levels varied from 1.0 to 3.5 percent, indicating that there were smokers in the group. Since smokers may have higher hemoglobin values than nonsmokers (18), the assumed hemoglobin value used in this experiment may not be valid.

By contrast, Vollmer *et al.* (19) have found that the effects of CO and high altitude hypoxia are not additive. Twenty subjects were used to study the effect of CO and high altitude hypoxia [3,050 to 4,575 m (10,000 and 15,000 feet)] on FFF, body sway, and size of the red visual field all during light activity. There was a significant impairment at simulated increased altitude, compared with performance at sea level, with and without exposure to CO. There was no significant difference between the mean test scores during hypoxia alone and the mean test scores following administration of CO. The increases in COHb were from 9 to 19 percent, with a final COHb ranging from 12 to 22 percent. This suggests that the resting COHb was three percent, and indicates that some of the subjects were smokers. Vollmer suggests that at 4,575 m (15,000 feet), any additional burden imposed by the presence of small amounts of COHb is masked by hypoxia compensatory mechanisms. Alternatively, he considers that it is possible that 9 to 19 percent COHb does not impose an important additional stress. At hypoxia corresponding to 4,750 m (15,500 feet), however, 4 of 17 subjects collapsed after being exposed to CO. The tests used in this study appear to be inadequate for predicting a serious cardiovascular reaction; nor can their sensitivity be ranked very high.

Most of the above studies were conducted before 1950. In 1966, Denison (20) demonstrated the significant effect hypoxia alone has on complex reaction times at a simulated altitude of 1,525 m (5,000 feet) during light work. At 1,525 m (5,000 feet), 8 of 10 subjects showed slower reaction times than 9 of 10 matched controls ($p < 0.05$). This effect of hypoxia was observed only during the early stages of learning the complex experimental task. Once the task had been learned, a simulated altitude up to 2,440 m (8,000 feet) had no effect. The effect of small amounts of CO on the learning of a new task at increased altitude remains to be determined.

Effects of Altitude on Carboxyhemoglobin Formation Kinetics

Coburn, Forster, and Kane (21) published a detailed theoretical analysis of the physiology and variables that determine blood carboxyhemoglobin values in man. Some of these are schematically depicted in Figure 1.

The basic relationship they describe is:

$$\frac{A\,[COHb]_t - \dot{V}_{CO}B - P_{ICO}}{A\,[COHb]_0 - \dot{V}_{CO}B - P_{ICO}} = e^{(-tA/V_bB)} = e^k$$

Defining terms:

$[COHb]_0$ = carboxyhemoglobin concentration at t = o units: ml CO/ml blood

e.g. : 1 g of Hb combines stoichiometrically with 1.34 ml of CO or O_2. Assuming 15 g% Hb: 0.5% COHb = (0.005) (1.34) (.15) = .005 ml CO/ml blood

$[COHb]_t$ = carboxyhemoglobin concentration at t = minutes exposure

e.g. : 2.5% COHb = (0.025) (1.34) (.15) = .005 ml CO/ml blood

$A = \bar{P}_{CO_2}/M\,[O_2Hb]$

$\bar{P}_{CO_2}$ = pulmonary capillary O_2 tension at sea level this ≅ 100 torr

M = relative affinity of Hb for CO and O_2

$[O_2Hb]$ = oxyhemoglobin in ml O_2/ml blood assuming 100% saturation of arterial blood

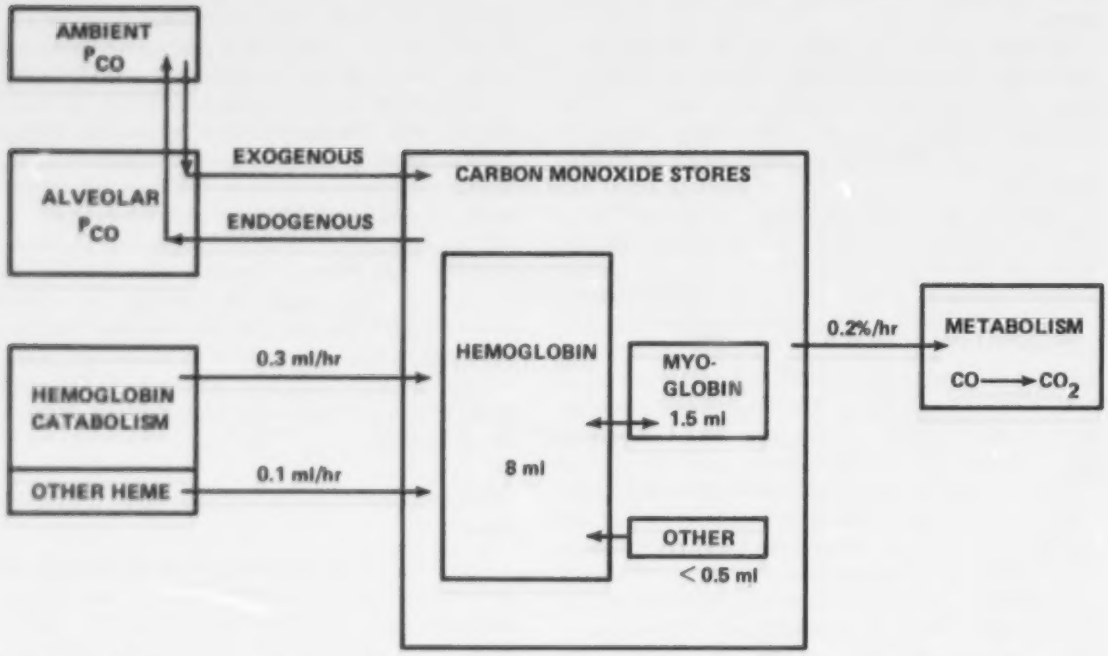

Figure 1. Diagrammatic summary of current concepts regarding variables that influence body CO stores. (22)

e.g. : $[O_2Hb] = (1.34)(.15) = .201$ ml O_2/ml blood

$$B = \frac{1}{D_L} + \frac{P_L}{V_A}$$

D_L = pulmonary diffusing capacity for CO ≅ 30 ml/min/torr

P_L = sum of partial pressures of alveolar gases excluding water vapor (47 torr at 37°C)

≅ 760 - 47 = 713 torr

V_A = alveolar ventilation

≅ 4200 ml/min at rest

V_b = blood volume ≅ 5,500 ml for 70 kilo man

P_{ICO} = partial pressure of CO in inspired air

k = Boltzmann's Constant

$$\text{ppm CO} = \frac{P_{ICO} \times 10^6}{\text{Barometric pressure}}$$

$\dot{V}_{CO}$ = rate of endogeneous CO production. This is related to heme metabolism which can vary considerably, as a function of red blood cell life span. Any factor reducing RBC survival elevates $\dot{V}_{CO}$. A reasonable average value for healthy adults = 0.007 ml/min.

The most useful rearrangements of the basic relationship are:

$$P_{ICO} = \frac{e^k [A(COHb)_o - \dot{V}_{CO}B]}{e^k - 1} + \left[\frac{\dot{V}_{CO}B - A(COHb)_t}{e^k - 1}\right]$$

whereby, exposure level needed to produce a given change in COHb over a given time can be calculated:

$$[COHb]_t = \frac{e^k [A(COHb)_o - \dot{V}_{CO}B - P_{ICO}]}{A} + \left[\frac{\dot{V}_{CO}B + P_{ICO}}{A}\right]$$

whereby, COHb resulting from a given exposure level for a given duration of exposure can be calculated.

Careful comparison of these relationships with available human exposure data confirms the general validity of using a theoretical model to solve the complicated problem of predicting COHb levels under a variety of experimental and clinical conditions.

Figure 2 shows a comparison of carboxyhemoglobin levels predicted by three empirical formulas and the theoretical model. During the first few hours of exposure, the formulas of Hanks (23) and Forbes (7, 24) agree very well with the model. Stewart's (25, 26) formula gives results which are higher than the others from the beginning and this difference is accentuated with time. Forbes' linear relationship is only applicable to about the first four hours of exposure. In order to examine the behavior of these formulas with long exposure times, the curves in Figure 3 were calculated. The inapplicability of both Forbes' and Stewart's formulas to long exposure times is dramatized. Results with Hanks' formula are virtually indistinguishable from those of the theoretical model for the first 10 hours, and with both models COHb levels come into equilibrium at about the same time with relatively little separation between the two asymptotes. Figure 4 shows the comparison of COHb equilibrium values for arbitrarily chosen exposures calculated from the formula of the California State Board of Public Health (22) and from the theoretical model. The points lie very close to the 45 degree line of identity.

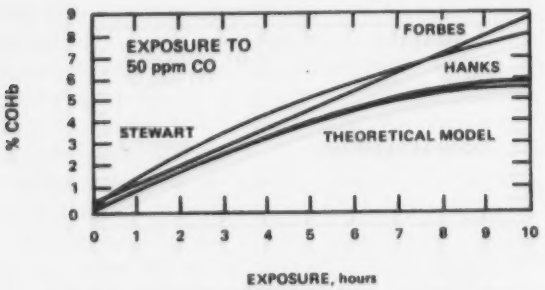

Figure 2. Comparison of CHOb levels predicted by three empirical formulas and a theoretical model.

It seems, therefore, that the California mathematical formula agrees very closely with available data when those data are properly interpreted. In addition, of course, the theoretical model allows computer simulation of CO exposure kinetics with the ability to vary a large number of input parameters. Great care must be exercised, however, in choosing appropriate and internally consistent values for these parameters as well as interpreting the results of modeling in a context that is physiologically reasonable.

The formula of Coburn *et al.* (21) becomes much more versatile and general if the alveolar air equation

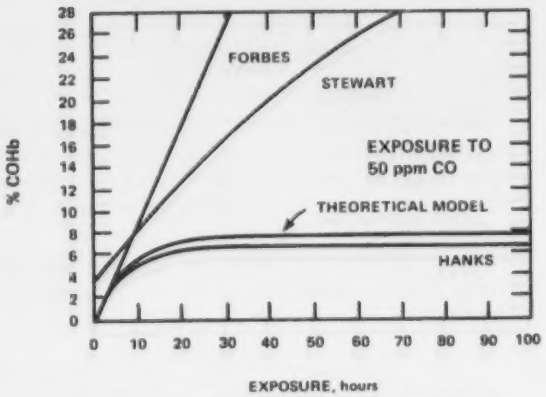

Figure 3. Comparison of COHb levels predicted by three empirical formulas and a theoretical model over long exposure times.

and certain empirical relationships between altitude and physiological variables (27) are included.

The alveolar equation is:

$$P_{A_{O_2}} = F_{I_{O_2}} (BP-47) - P_{A_{CO_2}} [F_{I_{O_2}} + 1 - F_{I_{O_2}}] \frac{}{R}$$

where $P_{A_{O_2}}$ = alveolar oxygen tension (torr),

$F_{I_{O_2}}$ = fraction of oxygen in inspired air,

BP = barometric pressure (torr),

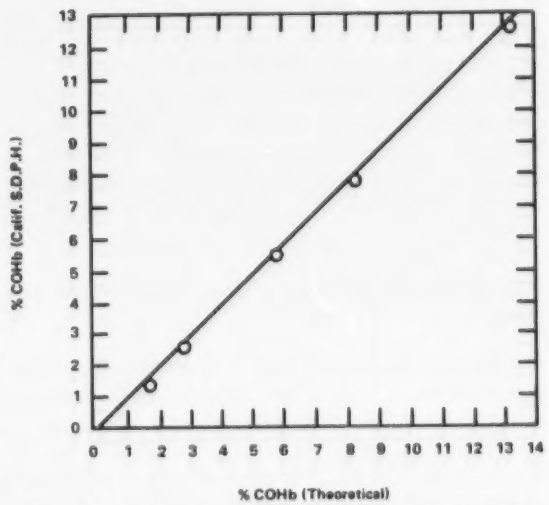

Figure 4. Comparison of equilibrium values calculated by the California State Department of Health's formula and the theoretical model.

$P_{A_{CO_2}}$ = alveolar CO_2 tension (torr), and

R = respiratory exchange ratio = $\dot{V}_{CO}/\dot{V}_{O_2}$.

With a negligible alveolar to arterial O_2 gradient, pulmonary capillary O_2 tension approximately equals alveolar O_2 tension. The alveolar air equation, therefore, can be used in the definition of factor A in the Coburn formula.

Simulation of the effect of altitude can be accomplished with the following empirical relationship:

$$P = 760\ e^{-(\frac{a}{7924})}$$

where P = atmospheric pressure (torr)

a = altitude above sea level in meters.

The calculated atmospheric pressure at altitude can thus be substituted for actual measured pressure in the alveolar air equation and in the conversion from ppm CO to P_{ICO}. It is important to remember that the conversion from mass to volume units in aerometry also involves atmospheric pressure. Thus, the details of instrument calibration must be known before one can decide whether or not it is appropriate to include an atmospheric pressure correction factor in calculating P_{ICO} from mass units.

$$\%\ RHb = 2.76\ e^{\frac{a}{2133}}$$

where % RHb is reduced hemoglobin formed as a result of exposure to altitude. This must be added to the % RHb present in a given individual at sea level and also taken into consideration when calculating factor A in the Coburn equation.

Permutt and Farhi (28) have emphasized the importance of considering the effect of CO exposure on tissue oxygenation, and this effect can also be calculated from known physiological variables. Thus, reliable mathematical modeling of the effect of CO exposure on tissue oxygenation is possible.

Effects of Altitude and Carbon Monoxide on the Fetus

It has been stated that the fetus under unpolluted sea level conditions lives at P_O comparable to the summit of Mt. Everest. (29) If this is the case, then decreases in fetal blood oxygen content, such as caused by four to five percent COHb, if prolonged, may cause brain damage and mental retardation. (30-32) The implications of these studies are great, particularly in the case of the expectant mother living at high altitudes who is exposed to moderately high levels of CO from auto exhaust or smoking.

ECOLOGY

From an ecological standpoint, a number of effects of altitude on air pollution should be considered. The pollutant conditions most frequently associated with altitude are confinement or entrapment within an inversion layer. The impact on the plant environment, thus, may be accentuated either because of an exposure of longer duration or a buildup of pollutant concentrations.

Within the first few hundred feet above the earth's surface the atmospheric composition is influenced be vegetation. Plants growing at higher altitudes are susceptible to the same pollutants as plants at lower levels. The pollutants reaching the vegetation at higher altitudes are the result of advection from air pollution sources at lower levels. Ozone transport from Los Angeles has been shown to be the cause of death of Jeffrey *(Pinus Jeffreyi)* and Ponderosa *(P. ponderosa)* pines in the San Bernardino and the Sierra Nevada Mountains. (33-36) Transport of sulfur dioxide could also cause vegetational injury at high altitudes.

Vegetational injury from both sulfur dioxide and ozone is dependent on pollutant entry into the leaves through the stomata. Environmental conditions, such as water stress, can result in closed stomata and protection from injury. (5) The vegetation of high altitude areas with low rainfall would probably be less susceptible to injury. Plant life may also remove pollutants from the atmosphere by presenting a barrier to particulates and curtailing their dispersion, or by adsorbing them. The latter processes may be important in scavenging pollutant gases or in sound absorption where noise is excessive. Pollutants removed via these mechanisms may be deposited into the soil. Although dependent on edaphic factors, such deposition does not usually enrich the soil.

Altitude, as defined in this report, relates primarily to ecosystems or their components located on plateaus or in mountainous regions at land elevations from 1,525 m (5,000 feet) up to at least 3,050 m (10,000 feet) or more. At these land elevations the distribution of biotic communities is complicated due to the diversity of physical conditions and due to the many species unique to mountain biomes. (37) Growing conditions for plants in the mountains become increasingly less favorable with increasing land elevation. (34) Because of the indigenous nature and lack of diversity of species, any pollutant stress may trigger exaggerated changes in these intricately balanced systems.

For example, solar insolation increases (38) and the light spectrum changes with increased altitudes. "The alpine environment is more severe than the arctic during the growing season...and higher ultraviolet radiation adds to this severity." (39) Biological ecosystem components at higher land elevations, although receiving more ultraviolet radiation than those at sea level, have adapted to such conditions. (38,40,41) Pirschle (42) studied plants from high land elevations in controlled chambers under varying light conditions. Those from alpine areas subjected to ultraviolet irradiation, although inhibited in their elongation, suffered no other damage, while test plants from sea level were killed. The amplitude of ultraviolet radiation is tempered by ozone concentrations.

Biological aerosols, suspensions of microorganisms in the air, and aeroallergens are ubiquitous in nature. The altitudes at which these organisms may exist or may concentrate and yet remain viable are shown in Figure 5. (43) Most show seasonal fluctuations, while some may occur at specific times only. Most exhibit extreme dispersion which is beneficial in maintaining the species since they are important parts of some of our ecosystems. On the other hand, undesirable species may become established in distant locations following aerosol transport or may act detrimentally in spreading disease or allergenic episodes within man's environment. (44-45)

Temperature inversions limit normal upward migration of microorganisms from the earth's surface, resulting in large microorganismal populations below the inversion.(46) Such confinement of disease-causing or allergenic microorganisms can result in episodic responses in the local human population.

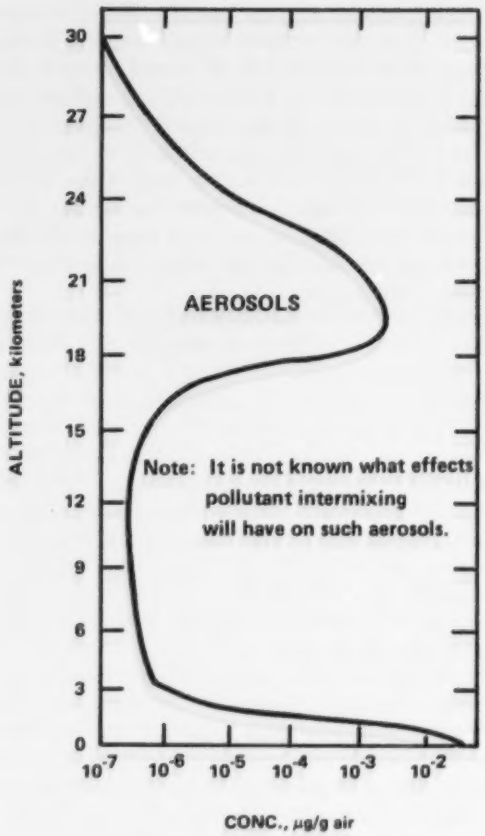

Figure 5. Concentration of aerosols with altitude. (43)

MATERIALS

No known research has been published in which the influence of elevation on air pollution damage to materials has been studied.

Several studies (47-56) concerning textile materials, however, have shown that the presence of sunlight produces a synergistic damage effect (i.e., the overall damage produced is greater than the sum of the damage effects produced by sunlight and certain pollutants individually). From a theoretical standpoint, therefore, it is reasonable to assume that because of increased ultraviolet radiation at higher altitudes, reaction rates between pollutants and materials would further accelerate. Of course the deteriorating action of sunlight alone, which for some materials is much more severe than that of pollutants alone, would also increase and could conceivably have greater significance at higher altitudes.

The lack of research precludes any definitive conclusions. However, a hypothetical conclusion is that for a given level of air pollution, damage to materials is probably greater (to an unknown extent) at higher than at lower altitudes because of the potentiating effect of the more intense insolation.

WEATHER, VISIBILITY, AND CLIMATE

In Chapter II, the impact of the increase in altitude on weather parameters was discussed. It is now appropriate to describe the effects of the variations of weather factors on air pollution.

The greater amount of solar radiation experienced at higher altitudes has the effect of enhancing the formation of secondary pollutants such as photochemical smog. The greater amount of ultraviolet radiation combined with increases in automobile traffic may account for the increased photochemical smog noted at major metropolitan areas in the Rockies. The greater amount of solar

radiation available also has the effect of enhancing the occurrence of convective air currents near the ground, thereby promoting a well-developed mixing layer daily. For example, at Denver throughout the year, the mean afternoon mixing heights vary from about 915 m (3,000 feet) above ground level in January to about 3,340 m (11,000 feet) in July. These mixing height characteristics for Denver are typical of the mountain and high land elevation areas of the West and exceed the mean mixing heights experienced by the rest of the nation.

Similarly, the loss of infrared radiation by the earth's surface at night is enhanced at high altitudes. Under clear skies the temperature profile at night is drastically changed by the rapid radiational cooling of the ground and the subsequent cooling of the layers of air near the surface. This creates an inversion. According to Hosler, (57) the occurrence of low-level inversions is greatest in the Appalachian and Rocky Mountain chains. Low-level inversions are present 30 to 50 percent of all hours in these areas. Under an inversion the atmosphere is stable, vertical interchange of air is inhibited, and pollutants tend to remain near the ground.

In the warm season of the year, with much ground heating, temperatures normally decrease rapidly with increasing height at high altitudes, but in winter, especially when the ground is covered by snow, temperature inversions near the earth's surface are frequent and persistent. Therefore, vertical dispersion is favored during the summer and limited during winter. Atmospheric conditions favoring pollution episodes occur in the winter in the Rocky Mountains and Great Basin areas of the western United States.

The rising air currents on the windward slopes of the mountains tend to disperse pollution through deep layers. Also the high frequency of precipitation, brought about by the forced ascent of air particularly at high altitudes in the coastal ranges, tends to wash out pollutants in the air mass. Snow is more efficient in washing out pollution than rain. Washout of pollutants, and damage to surface receptors, may occur if the concentration of pollutants in the air mass is high. Moreover, the pollution may find its way into lakes and streams and contribute to the contamination of these waters. Acidic particulate species may adversely affect not only lakes and streams, but also soil conditions in some areas.

In general, the visibility within air masses over the higher altitudes in the western United States remains good. However, in the vicinity of large metropolitan areas and near large power plant complexes, reduction in visibility is being observed. The major visibility problems at the present time occur where large metropolitan areas, with a multitude of pollutant sources, are located in topographical depressions which favor the occurrence of low wind speeds and stable air near the earth's surface. The high frequency of stagnating air masses in the late fall and winter favors the occurrence of air pollution episodes in metropolitan areas such as Denver. (58-61)

REFERENCES

1. Merritt, J. H. and M. A. Medina. Altitude Induced Alterations in Drug Action and Metabolism. Life Sci. *7*:1163-1169, 1968.
2. Lenfant, C. and K. Sullivan. Adaptation to High Altitude. N. Eng. J. Med. *284*:1309, 1971.
3. Folk, G. E., Jr. Introduction to Environmental Physiology. Lea and Febiger, Philadelphia, 1966.
4. Hecht, H. H. A Sea Level View of Altitude Problems. Am. J. Med. *50*:703-708, 1971.
5. Robinson, S. M. Effect of Simulated Altitude on Lethality of Sympathomimetic Amines. Toxicol. Appl. Pharmacol. *15*:304-309, 1969.
6. Medina, M. A. and J. H. Merritt. Drug Metabolism and Pharmacologic Action in Mice Exposed to Reduced Barometric Pressure. Biochem. Pharmacol. *19*:2812-2816, 1970.
7. Forbes, W. H., F. Sargent, and F. J. W. Roughton. The Rate of Carbon Monoxide Uptake by Normal Men. Amer. J. Physiol. *143*:594-608, 1945.
8. Root, W. S. Carbon Monoxide. *In*: Handbook of Physiology, Section 3: Respiratory. Fenn, W. O. and H. Rahn (eds.). American Physiological Society, Washington, D.C. 1965, pp. 1087-1098.
9. Pitts, G. C. and N. Pace. The Effect of Blood Carboxyhemoglobin Concentration on Hypoxia Tolerance. Amer. J. Physiol. *148*:138-151, 1947.
10. Wagner, J. A., S. M. Horvath, W. H. Cottle, and J. F. Bedi. Separate and Combined Effects of Altitude "3048 m" and Elevated Blood Carboxyhemoglobin "% HbCO" on Work Performance of Cigarette Smokers. Fed. Proc. Am. Soc. Exp. Biol. *36*:533, 1977.
11. A Comparison of Prolonged Exposure to Carbon Monoxide and Hypoxia in Man. Astrup, P. and H. G. Pauli (eds.). Scand. J. Clin. Lab. Invest. *24* (Suppl. 103): 1-71, 1968.
12. Mills, E. and M. W. Edwards, Jr. Stimulation of Aortic and Carotid Chemoreceptors During Carbon Monoxide Inhalation. J. Appl. Physiol. *25*(5):494-502, 1968.
13. Weiser, P. C., C. G. Morrell, D. W. Dickey, T. L. Kurt, and G. J. A. Cropp. Effects of Low-Level Carbon Monoxide Exposure on the Adaptation of Healthy Young Men to Aerobic Work at an Altitude of 1610 Meters. *In*: Environmental Stress: Individual Adaptation. Folinsbee, L. J. (ed.), Academic Press, New York (In Press).
14. Lindgren, S. A. A Study of the Effects of Protracted Occupational Exposure to Carbon Monoxide with Special Reference to the Occurrence of the So-Called Chronic Carbon Monoxide Poisoning. Acta Med. Scand. (Stockholm) *167* (Suppl. 356):1-135, 1961.
15. McFarland, R. A., F. J. W. Roughton, M. H. Halperin, and J. I. Niven. The Effects of Carbon Monoxide and Altitude on Visual Thresholds. J. Aviat. Med. *15*(6):381-394, 1944.
16. Halperin, M. H., J. I. Niven, R. A. McFarland, and F. J. W. Roughton. The Time Course of the Effects of Carbon Monoxide on Visual Thresholds. J. Physiol. (London) *146*(3): 583-593, 1959.

17. Lilienthal, J. L. and C. H. Fugitt. The Effect of Low Concentrations of Carboxyhemoglobin on the Altitude Tolerance of Man. Amer. J. Physiol. *145*(3):359-364, 1946.
18. Eisen, M. E. and E. C. Hammond. The Effect of Smoking on Packed Cell Volume, Red Blood Cell Counts, Hemoglobin and Platelet Counts. Can. Med. Assoc. J. *75*(6):520-523, 1956.
19. Vollmer, E. P., B. G. King, J. E. Birren, and M. B. Fisher. The Effects of Carbon Monoxide on Three Types of Performance at Simulated Altitudes of 10,000 and 15,000 Feet. J. Exp. Psychol. *36*(3):244-251, 1946.
20. Denison, D. M., F. Ledwith, and E. C. Poulton. Complex Reaction Times at Simulated Cabin Altitudes of 5,000 Feet and 8,000 Feet. Aerospace Med. *37*:1010-1013, 1966.
21. Coburn, R. F., R. E. Forster, and P. B. Kane. Considerations of the Physiology and Variables that Determine the Blood Carboxyhemoglobin Concentration on Man. J. Clin. Invest. *41*:1899-1910, 1965.
22. Goldsmith, J. R. and S. A. Landaw. Carbon Monoxide and Human Health. Science *162*(3860):1352-1359, 1968.
23. Hanks, T. G. Human Performance of a Psychomotor Test as a Function of Exposure to Carbon Monoxide. Ann. N.Y. Acad. Sci. *174*:421-424, 1970.
24. Forbes, W. H. Carbon Monoxide Uptake via the Lungs. Ann. N. Y. Acad. Sci. *174*:72-75, 1970.
25. Stewart, R. D., J. E. Peterson, E. D. Baretta, R. T. Bachand, M. J. Hosko, and A. A. Herrmann. Experimental Human Exposure to Carbon Monoxide. Arch. Environ. Health *21*:154-164, 1970.
26. Stewart, R. D. The Effect of Carbon Monoxide on Humans. Ann. Rev. Pharmacol. *15*:409-423, 1975.
27. Larsen, R. I. Determining Basic Relationships Between Variables. *In*: Environmental Measurements: Valid Data and Logical Interpretation. Public Health Service Publication No. 999-AP-15. U. S. Government Printing Office, pp. 251-263, 1964.
28. Permutt, S. and L. Farhi. Tissue Hypoxia and Carbon Monoxide. *In*: Effects of Chronic Exposure to Low Levels of Carbon Monoxide on Human Health, Behavior, and Performance. National Academy of Sciences-National Academy of Engineering, Washington, D.C., 1969, pp. 18-25.
29. Beard, R. R. Toxicological Appraisal of Carbon Monoxide. J. Air Pollut. Control Assoc. *19*:722-732, 1969.
30. Goldstein, H. Factors Influencing the Height of Seven Year Old Children-Results from the National Child Development Study. Human Biol. *43*:92-222, 1971.
31. Denson, R. J. L. Manson, and M. A. Mac-Watters. Hyperkinesis and Maternal Smoking. Can. Psychiatr. Assoc. J. *20*:183-187, 1975.
32. Longo, L. D. The Biological Effects of Carbon Monoxide on the Pregnant Woman, Fetus and Newborn Infant. Am. J. Obstet. Gynecol. *129*(1):69-103, 1977.
33. Ozone and Other Photochemical Oxidants *In*: Ecosystems. National Research Council, Committee on Medical and Biological Effects of Environmental Pollutants. National Academy of Sciences, Washington, D. C., 1977, pp. 586-642.
34. Williams, W. T., M. Brady, and S. C. Willison. Air Pollution Damage to the Forests of the Sierra Nevada Mountains of California. J. Air Pollut. Control Assoc. *27*:230-234, 1977.
35. Palmer, T. Y., L. A. Smith, and J. Neirinck. Ozone in the Valleys of the High Sierra Nevada. *In*: International Conference on Environmental Sensing and Assessment. Vol. 2. Institute of Electrical and Electronics Engineers, New York, 1976, pp. 32-37.
36. Mudd, J. B. and T. T. Kozlowski (eds.). Responses of Plants to Air Pollution. Academic Press, New York, 1975.
37. Odum, E. P. Fundamentals of Ecology. Third Edition, W. B. Saunders Co., Philadelphia, 1971.
38. Traquilline, W. The Physiology of Plants at Higher Altitudes. Ann. Rev. Plant Physiol. *15*:337-345, 1964.
39. Bliss, L. C., A Comparison of Plant Development in Microenvironments of Artic and Alpine Tundras. Ecol. Monogr. *26*:303-337, 1956.
40. Billings, WW. D. and H. A. Mooney. The Ecology of Artic and Alpine Forests. Biol. Rev. *43*:481-529, 1968.
41. Treshow, M. Environment and Plant Response. McGraw-Hill, Inc., New York, 1970.
42. Pirschle, K. Weitere Beobachtungen Über den Einsluss von Langwelliger und Kurzwelliger UV-Strahlung auf höhere Pflanzen, besonders polyploide und hochalpine formen "Stellaria, Epilobium, Arenaria, Silene." Biol. Zentralbl. *61*:452, 1941.
43. Newall, R. E. The Global Circulation of Atmospheric Pollutants. Sci. Am. *224*:32-42, 1971.
44. Finkelstein, H. Preliminary Air Pollution Survey of Biological Aerosols. Litton Report, USDHEW, NAPCA, APTD Publication No. 69-30, U.S. Government Printing Office, 1969.
45. Finkelstein, H. Preliminary Air Pollution Survey of Aeroallergens. Litton Report, USDHEW, NACPA, APTD Publication No. 69-23, U.S. Government Printing Office, 1969.
46. Fulton, J. D. and R. B. Mitchell. Microorganisms of the Upper Atmosphere. II. Microorganisms in Two Types of Air Masses at 690 Meters Over a City. Appl. Microbiol. *14*:232-236, 1966.
47. Morris, M. H. and B. Wilsey. The Effect of Soil on the Photochemical Degradation of Cotton. Text. Res. J. *29*:971-974, 1959.
48. Morris, M. A. and M. A. Young. The Exposure of Soiled Cotton to Sunlight: Degradation and Color Changes. Text. Res. J. *35*:178-180, 1965.
49. Morris, M. A., B. W. Mitchell, and T. Aas-Wang. The Effect of an Airborne Soil on the Photochemical Degradation of Wool. Text. Res. J. *32*:723-727, 1962.
50. Morris, M. A. and B. W. Mitchell. The Effect of an Airborne Soil on the Photochemical Degradation of Nylon. Text. Res. J. *31*:448, 1961.
51. Little, A. H. The Effect of Light on Textiles. J. Soc. Dyers Colour *80*:527-534, 1964.
52. Fye, C., K. Flaskerud, and D. Savelle. Effect of an SO^2 Atmospheric on the Breaking Strength of Fabrics of Different Fiber Content. Am. Dyest. Rep. *58*:16-19, 1969.
53. Zeronian, S. H. Reaction of Cellulosic Fabrics to Air Contaminated with Sulfur Dioxide. Text. Res. J. *40*:695-698, 1970.
54. Zeronian, S. H., K. W. Alger, and S. T. Omaye. Reaction of Fabrics Made from Synthetic Fibers to Air Contaminated with Nitrogen Dioxide, Ozone, or Sulfur Dioxide. *In*: Proceedings of the Second International Clean Air Congress. Academic Press, New York, 1971, pp. 468-476.
55. Zeronian, S. H. The Effect of Light and Air Contaminated with Sulfur Dioxide on the Surface of Nylon 66 Fibers. Text. Res. J. *41*:184-185, 1971.
56. Morris, M. A., M. A. Young, and T. A. Molvig. The Effect of Air Pollutants on Cotton. Text. Res. J. *34*:563-564, 1964.
57. Hosler, C. R. Low Level Inversion Frequency in the Contiguous United States. Mon. Weather Rev. *89*:319-339, 1961.

58. Van Valin, C. C. and R. F. Pueschel. Nucleation Characteristics of Denver Aerosols *In*: Denver Air Pollution Study-1973: Proceedings of a Symposium. Vol. 1. EPA-600/9-76-007a. USEPA, Research Triangle Park, N.C., 1976. pp. 876-899.

59. Middleton, P. B. and J. R. Brock. Atmospheric Aerosol Dynamics: The Denver Brown Cloud. *In*: Denver Air Pollution Study-1973: Proceedings of a Symposium. Vol. 1. EPA-600/9-76-007a. USEPA, Research Triangle Park, N. C., 1976, pp. 101-139.

60. Waggoner, A. P. and R. J. Charlson. Measurements of Aerosol Optical Properties. *In*: Denver Air Pollution Study-1973: Proceeding of a Symposium. Vol. 2. EPA-600/9-77-001. USEPA, Research Triangle Park, N.C., 1977, pp. 35-55.

61. Waggoner, A. P. The Brown Cloud of Denver. *In*: Denver Air Pollution Study-1973: Proceedings of a Symposium. Vol. 2. EPA-600/9-77-001. USEPA, Research Triangle Park, N.C., 1977, pp. 159-167.

APPENDIX A

EFFECTS OF ALTITUDE ON AEROSOL DYNAMICS

The atmospheric aerosol processes of interest that might be affected by high altitude are: nucleation, condensation, dry and wet deposition, coagulation, and gas-to-aerosol conversion. Aerosol instrumentation response and performance might be changed for devices calibrated at sea level and used at high land elevations. Also, aerosol lung deposition efficiencies at high altitudes might be changed with respect to those at sea level. Modification of the rates of these processes, instrumentation performance, and lung deposition efficiencies will be discussed. However, variations in source emission characteristics as a function of altitude will not be addressed here, nor will the performance of industrial devices for primary aerosol control (such as electrostatic precipitators and wet scrubbers).

The important mass transport parameters for air that change with altitude and that might be expected to influence aerosol dynamics are: air density (or molecular mean-free path), air viscosity, the acceleration due to gravity, and temperature. The change in density, molecular mean-free path, and viscosity for increasing altitude is shown in Table A-1. The viscosity is essentially constant down to pressures below 0.3 kg m^{-2} (0.02 torr). Also, over the contiguous 48 states, the acceleration due to gravity varies within the range of 9,790 to 9,809 m sec^{-2}, which for our purposes can be considered constant. Thus, the only mass transport parameters for air exhibiting significant dependence on altitude are density (molecular mean-free path) and temperature.

Processes

Since an exact theory for nucleation is lacking for heterogeneous mixtures, an equation for the production rate of critical nuclei in the atmosphere as a function of the collision frequency, temperature, and the Gibbs free energy of adsorption cannot be stated. The heterogeneous nucleation rate per unit of substrate surface area decreases as pressure decreases. However, the dependence of the rate on temperature and the Gibbs free energy may be more important and could result in increases or decreases at high altitude cities compared to sea level for the same mass concentration of nucleating monomers. The rate of condensation of low-vapor pressure gases onto existing aerosols (4) can be described by

$$F = \frac{\phi}{4\pi R^2} = -\frac{D\,(n_\infty - n_s)R^{-1}}{1 + c\lambda/R}$$

where F = mass flux per unit area to a spherical particle,
ϕ = mass flux to a spherical particle of radius R,
R = radius of sphere,

TABLE A-1. MASS TRANSPORT PARAMETERS (T = 293° K)

Elevation, meters	Standard [a] Pressure, kg m^{-2}	Density [b], kg m^{-3}		Molecular Mean-Free Path [b] nm		Viscosity [c], kg m^{-1} sec^{-1}	
		242° K	293° K	242° K	293° K	242° K	293° K
Sea level	10.33 (760 torr)	1.56	1.29	54.0	65.3	1.54	1.81
1,524 m (5,000 ft)	8.56 (630 torr)	1.30	1.07	64.8	78.8	1.54	1.81
3,048 m (10,000 ft)	7.07 (520 torr)	1.06	0.88	79.2	95.4	1.54	1.81

[a] From ref. 1 [b] From ref. 2 [c] From ref. 3

D = gaseous diffusion coefficient of condensing specie,
c = constant (≈ 1.5),
λ = molecular mean-free path,
n_∞ = concentration of condensing specie far from the particle's surface, and
n_s = concentration of condensing specie at the particle's surface.

The ratio of fluxes at sea level and at 1,524 m has been calculated for T = 20° C (293°K), assuming that the mass concentrations of the condensing specie are equal. The ratios are presented in Table A-2 for various aerosol diameters.

TABLE A-2. RATIO OF FLUXES
(T = 20°C [293°K])

Diameter, μm	0.01	0.1	1
$\frac{\phi\ (1{,}524\ m)^a}{\phi\ (sea\ level)^b}$	1.00	1.00	1.17

[a]Pressure = 8.56 kg m^{-2} [b]Pressure = 10.33 km m^{-2}

The half-life for molecular collisions with urban aerosols is on the order of a second; thus, condensation rates would be expected to be approximately the same for sea level and high altitude cities for T = 20°C (293°K). Lowering the temperature (at constant pressure) from 20°C (293°K) to -31°C (242°K) reduces the gaseous diffusion coefficient by about 30 percent, but also significantly lowers the vapor pressure (n_s) of the condensing species. The two effects act in opposition and for various species the rate may be increased or decreased. Because the half-life for collisions is so short, the change in the condensation rate due to pressure and temperature changes is probably not significant, although a decrease in the condensation rate may cause an increase in the nucleation rate. For both sea level and high altitudes, a lowering of the temperature depresses the equilibrium vapor pressure and may result in large shifts of condensible vapors from the gas phase to aerosols.

The process of coagulation changes the atmospheric aerosol size distribution. The decrease in the aerosol number concentration can be expressed by the basic equation

$$dn/dt = -K_o n^2$$

for a monodisperse aerosol, where

n = aerosol number concentration, and
K_o = coagulation constant (monodisperse).

For polydisperse systems,

$$dn(r_1,r_2,t)/dt = -K(r_1,r_2)n(r_1,t)n(r_2,t),$$

where $K(r_1,r_2,)$ is the coagulation constant for particles of radius r, with particles of radius r_2, and is a function of the mean thermal speeds, concentration gradient thicknesses, and particle diffusion coefficients. With the formula given by Fuchs (5), the ratio of coagulation coefficients for various combinations of atmospheric pressure and temperature can be calculated, as shown in Table A-3.

TABLE A-3. RATIO OF COAGULATION COEFFICIENTS

Diameters, μm	0.01, 0.02	0.02, 0.1	0.02, 0.2
$\frac{K_B{}^a}{K_A{}^b}$	1.03	1.36	1.20
$\frac{K_C{}^c}{K_A{}^b}$	0.92	0.97	0.97

[a]A: T = 293° K, l = 0.065 μm, μ = 1.81 kg m^{-1}sec^{-1}
[b]B: T = 293° K, l = 0.079 μm, μ = 1.81 kg m^{-1}sec^{-1}
[c]C: T = 242° K, l = 0.065 μm, μ = 1.54 kg m^{-1}sec^{-1}

At high altitude as compared to low altitude at the same temperature, the coagulation rates for fine aerosols will be faster, perhaps by as much as 20 to 40 percent. However, when the temperature at high altitude is low (-31°C), the rates are essentially the same.

The process of atmospheric dry deposition is not completely understood. However, in general terms, the deposition of aerosols with diameters greater than about 0.3 μm is explained in terms of sedimentation and impaction. For sedimentation, the terminal fall velocity for viscous and non-viscous flow is (5)

$$V_s = \left[\frac{8R\ (\rho_p - \rho_a)g}{3\rho_a C_D}\right]^{1/2}$$

where V_s = terminal fall velocity,
R = radius,
ρ_p = density of particle,
ρ_a = density of air,
g = acceleration due to gravity, and
C_D = drag coefficient.

Usually, for atmospheric aerosols, the particle density (ρ_p) is in the range 1 to 2.5 g/cm^3, which is large in comparison to the air density (0.00129 g/cm^3 at sea level). Thus, in the above equation, the term (ρ_p-ρ_a)

can be replaced by ρ_p for atmospheric applications. For viscous flow, the drag coefficient is

$$C_D = 24/Re$$

where Re = particle Reynolds number
$= 2VR\rho_a/\eta$,
V = fall velocity, and
η = air viscosity.

Therefore, the terminal settling for viscous flow is

$$V_s = \frac{2}{9}\frac{R^2 g\rho_p}{\eta},$$

which is independent of the air density. The values for viscosity (η) and acceleration due to gravity (g) are constant for changes in pressure, causing the sedimentation rates for viscous flow to be the same for sea level and high altitude sites (assuming constant temperature). Sedimentation in nonviscous flow must also be considered since the atmosphere is in turbulent motion. The drag coefficient for non-viscous flow must account for the air inertia terms in the equations of motion, making it more complex. For a force of 1g on the particle, the above equation can be written as

$$C_D Re^2 = 32\ \rho_a\rho_p R^2 g/3\eta^2.$$

Davies' (6) empirical expression (not shown) for the Reynolds number as a function of $C_D Re^2$ was used to calculate the settling velocities for non-viscous flow at sea level and 1,524 m at a temperature of 20°C (293°K); the particle's density was taken to be 2.5 kg/m^3. The ratios of settling velocity are in Table A-4. The settling velocity for particles with a geometric diameter of 100μm is approximately four percent greater at an altitude of 1,524 m than at sea level for the same temperature; for smaller diameters, the ratio decreases to a limit of unity. The settling velocity at 1,524 m for a pressure of 8.56 kg m^{-2} and a temperature of -32°C (241.6°K) has been calculated and its ratio to the settling velocity at sea level for a pressure of 10.33 kg m^{-2} and a temperature of 20°C (293°K) is given in Table 5.

TABLE A-4. NON-VISCOUS FLOW SETTLING VELOCITY RATIOS
(T = 293°K, ρ_p = 2.5 kg m^{-3})

Diameter, μm	1	25	50	75	100
V_s (1,524 m)[a] / V_s (sea level)[b]	1.00	1.0	1.02	1.03	1.04
V_s (sea level)[b], cm sec^{-1}	0.007	4.6	17.3	34.3	54.7

[a]Pressure = 8.56 kg m^{-2}, ρ_a = 107 kg m^{-3}
[b]Pressure = 10.33 kg m^{-2}, ρ_a = 1.29 kg m^{-3}

TABLE A-5. NON-VISCOUS FLOW SETTLING VELOCITY RATIOS (ρ_p = 2.5 kg m^{-3})

Diameter, μm	1	25	50	75	100
V_s (1,524 m)[a] / V_s (sea level)[b]	1.3	1.2	1.2	1.1	1.0

[a]Pressure = 8.56 kg m^{-2}, ρ_a = 1.29 kg m^{-3}, T = 242°K, μ = 1.54 kg m^{-1} sec^{-1}
[b]Pressure = 10.33 kg m^{-2}, ρ_a = 1.29 kg m^{-3}, T = 293°K, μ = 1.81 kg m^{-1} sec^{-1}

Settling for aerosols with diameters less than 75 μm at high altitudes during cold periods will be greater (10 to 20 percent) than at low altitudes during warm periods, but at equal temperatures there is very little difference.

Impaction is also an important dry deposition process for aerosols with diameters in the range 0.3 to 100 μm. Impaction of aerosols onto environmental surfaces can be thought of as a function of the *stop distance*, which is the path length traversed by a particle that is in motion and is diverted into still air. The *stop distance*, L, is expressed as (5)

$$L = \frac{2V_o r^2 \rho_p}{9\eta}$$

where V_O = initial velocity of the particle upon entering still air zone. Simplistically, one can visualize the aerosol to be in turbulent motion in the atmosphere and directed toward an environmental object that has a thin viscous sublayer (thickness = λ) of air at its surface. If the aerosol has a *stop distance* (L) that is greater than λ, it will be impacted; if not, it will likely be swept away by the turbulent air. In the above equation, the viscosity is independent of pressure; thus, the *stop distance* for high altitude and sea level is constant for particles with the same radii, density, and initial velocity. However, the thickness, λ, of the viscous sublayer (5) is approximately inversely proportional to the fluid Reynolds number (Re_f) as

$$\lambda \tilde{\propto} Re_f^{-1} \propto \rho_a^{-1}.$$

Thus, the ratio of thickness of the viscous sublayer for 1,524 m to sea level is

$$\frac{\lambda\ (1{,}524\ \text{m})}{\lambda\ (\text{sea level})} \approx \frac{\rho_a\ \ (1{,}524\ \text{m})^{-1}}{\rho_a\ \ (\text{sea level})} \approx 1.20$$

The particle efficiency of penetration through the viscous sublayer is inversely proportional to λ; thus, the dry deposition flux due to impaction is expected to be approximately 20 percent less at an elevation of 1,524 m with respect to sea level at constant temperature 20°C (293°K). However, for a

temperature of -31°C (242°K) at an altitude of 1,524 m and for a temperature of 20°C (293°K) at sea level, the ratio becomes unity; there should be no difference in the dry deposition flux due to impaction. It is difficult to resolve the contributions of settling and impaction to dry deposition of aerosols in size range $0.3 < \text{diameter} < 100\ \mu m$. Most likely, dry deposition velocities at high altitudes and sea level will be approximately the same for particles in the range $0.3 < \text{diameter} < 100 \mu m$.

Settling and impaction are generally thought to be unimportant for the dry deposition of atmospheric aerosols with diameters less than approximately 0.3 μm. The dry deposition of these fine aerosols can be visualized as follows: the fine aerosols are in a turbulent eddy that moves toward an environmental object that has a variable thin viscous sublayer (thickness = δ) of air at its surface. The fine aerosols are transported to the edge of the laminar layer, and may be deposited only by diffusing across the viscous sublayer. The dry deposition flux of fine aerosol to the surface is (5)

$$N = D \frac{dn}{dz}$$
$$= D (n_\delta - n_s) / \delta$$

where N = flux of aerosol to the surface,

n_δ = aerosol concentration at the edge of the viscous sublayer of thickness, δ,

n_s = aerosol concentration at a distance of one molecular mean-free path of air from the surface of the environmental object, and

D = particle's Brownian diffusion coefficient.

Since, $n_s = O$, the equation for the flux becomes

$$N = D n_\delta / \delta.$$

This equation must be integrated over the size distribution to account for the dependence of the diffusion coefficient on the particle radius. Both the diffusion coefficient and thickness of the viscous sublayer vary with altitude. The diffusion coefficient, D, is

$$D = kTB$$
$$B = [1 + A\frac{l}{r} + Q\frac{l}{r}\exp(-br/l)](6\pi\eta r)^{-1}$$

where k = Boltzmann's constant

T = temperature, °K

B = particle mobility

A = 1.246

l = molecular mean-free path of air

Q = 0.42

b = 0.87

The diffusion coefficient is independent of the density of the aerosol, but dependent on changes in T, l, and μ. The ratios for diffusion coefficient for an altitude of 1,524 m and sea level are shown in Table A-6.

Since the viscous sublayer is inversely proportional to the air density, the ratio of dry deposition for fine aerosols is shown in Table A-7. Thus, for a temperature of 20°C (293°K) at upper altitude and at sea level, the dry deposition rate of fine aerosol would be about the same. However, if the temperature at the higher altitude is 242°K, then the fine aerosol deposition rate will be about 20 percent lower than at sea level.

Wet deposition of gases and aerosols is difficult to compare for high and low altitudes, since in-cloud scavenging (*rainout* and *snowout*) and below-cloud scavenging (*washout*) are complex phenomena. The removal efficiencies depend strongly on such parameters as the raindrop or snowflake size distribution, collision efficiencies, electrical charge, crystal type, shape, fall speed, etc. Since these processes are still not completely understood, speculations regarding differences related to altitude will not be made.

Aerosol Instrumentation

The performance of aerosol samplers and monitors calibrated at lower altitudes may be affected when

TABLE A-6. RATIO OF DIFFUSION COEFFICIENT

Diameter, μm	0.005	0.01	0.05	0.1	0.5
$\frac{D\ (1{,}524\ m)^a}{D\ (sea\ level)^b}$	1.20	1.20	1.20	1.13	1.05
$\frac{D\ (1{,}524\ m)^c}{D\ (sea\ level)^b}$	0.73	0.74	0.81	0.87	0.96
D (sea level)^b cm^2/sec	2.08×10^{-3}	5.28×10^{-4}	2.37×10^{-5}	6.85×10^{-6}	6.26×10^{-7}

[a] T = 293°K l = 78.8 nm, μ = 1.81 kg m^{-1} sec^{-1}
[b] T = 293°K l = 65.3 nm, μ = 1.81 kg m^{-1} sec^{-1}
[c] T = 293°K l = 84.8 nm, μ = 1.54 kg m^{-1} sec^{-1}

TABLE A-7. RATIO OF FINE AEROSOL FLUX

Diameter, μm	0.005	0.01	0.05	0.1	0.5
N (1,524 m)[a] / N (sea level)[b]	1.00	1.00	0.98	0.94	0.87
N (1,524 m)[c] / N (sea level)[b]	0.73	0.74	0.81	0.87	0.96

[a] T = 293°K, ρ_a = 1.07 kg m^{-3}
[b] T = 293°K, ρ_a = 1.29 kg m^{-3}
[c] T = 242°K, ρ_a = 1.30 kg m^{-3}

used at high altitudes. The devices that will be affected are those whose principle employs the resistance of the air to the motion of the aerosol particles being sized. Such devices include: sedimentation chambers, horizontal and vertical elutriators, impactors, virtual impactors, cyclones, diffusion batteries, electrical mobility analyzers, etc. The parameters that can be expected to modify the performance are viscosity (due to temperature differences) and the mean-free path of air. Sedimentation chambers and horizontal and vertical elutriators are not now commonly used for determining atmospheric size distributions or for aerosol classification; however, they are of historic interest. Their performance depends on the sedimentation velocity and air flow profile (for elutriators). The changes in sedimentation velocity as a function of altitude can be treated directly and has been discussed above. The flow profile within the elutriator can be thought of as a function of the fluid Reynolds number

$$Re_f = \rho_a v L / \mu$$

where L = characteristic dimension of conduit

v = average fluid velocity.

If the dimension, L, is constant, for a constant velocity, v, the Reynolds number depends on air density and viscosity; however, difference between the Reynolds number for high and low altitudes and various temperatures is expected to be less than 10 percent. Thus, significant changes in performance due to modification of the flow profile are not expected.

Cascade impactor is probably the most commonly used research device for aerosol classification. The efficiency of an impaction stage depends on the Stokes number (7),

$$Stk = C\rho_p v d^2 / 18\,\mu L$$

where C = Cunningham slip correction factor,

v = average velocity of air in jet, and

L = diameter (or width) of jet.

A stage is usually characterized by experimentally determining the diameter (d_{50}) for which 50 percent of the particles are impacted. (For round jets, d_{50} corresponds to Stk = 0.2.) For aerosols with diameter greater than 0.2 μm, C does not change significantly with altitude (pressure and temperature) to be of concern. However, the viscosity is temperature-dependent and a change from 20°C (293°K) to -31°C (242°K) will lower the d_{50} values by about eight percent for a constant volume flowrate. Also, it can be expected that the cut point diameter for virtual impactors should exhibit a similar temperature dependence. The dependence of flow profiles on the fluid Reynolds number (which probably varies less than 10 percent) is not expected to be important with regard to performance.

There is not yet an exact theory for the operation of cyclones. Fuchs (5) has made an estimate of the efficiency (E) of cyclones, considering turbulent flow:

$$E = 1 - \exp(-\pi v \tau s / 2h)$$

where v = average flow velocity,

s = number of turns of spiral,

h = width of inlet, and

τ = relaxation time

$= 2 r^2 \rho_p / 9\mu$.

Although the equation cannot be considered to be exact, it should be suitable for deducing the influence of altitude factors on the performance of cyclones. For a constant volume flow rate, the only parameter that needs to be considered is the viscosity. Since viscosity is independent of pressure, only temperature variations are imporatant. From the above equation, it is estimated that a cyclone with a 50 percent efficiency for particles with a 4-μm diameter, operated at 20°C (293°K), will have an efficiency of 56 percent if operated at -31°C (242°K) with the same volume flow rate (uncorrected). However, if the cyclone is operated at constant air mass flow rate, its efficiency is estimated to be 63 percent at -31°C (242°K) for 4μm diameter particles at 1,524 m, compared to 50 percent at sea level.

The determination of aerosol size distributions for particles with a diameter less than 0.2 μm has been performed with diffusion batteries (5). The technique is based on a measurement of the decrease in aerosol number concentration as a function of length of the

capillary conduit; the depletion of aerosol results from diffusion deposition on the conduit walls. Thus, the technique is dependent upon the aerosol diffusion coefficient, which is a function of pressure and temperature. The correction can be made to the diffusion coefficient as described above in the section on dry deposition.

Electrical mobility analyzers are coming into frequent use for aerosol size measurement of particles with diameters less than 0.5 μm. There are two sources of possible performance modification for this device: the aerosol charging section and the aerosol drift tube. Usually, the charging section is operated with a constant corona current to yield an *ion density × charging time* (N_0t) product of 10^6. The degree of aerosol charging (number of particles charged and charge distribution) depends on the ion mobility, which is proportional to the molecular mean-free path. An instrument calibrated at sea level and operated at constant corona current at an altitude of 1,524 m will have its (N_0t) decreased by 20 percent, due to the 20 percent increase in ion mobility. The effect on aerosol charging is nonlinear, and the charge distribution on aerosol is very sensitive for small (N_0t) values of 10^6 or less. If a (N_0t) value of 10^7 (at sea level) is employed, the modification of charge distribution is less, but greater multiple charging occurs, lowering the resolution of the instrument. In the drift tube, sizing is inferred from the quantity of charged aerosol that passes through the tube as a function of applied electrical field. Thus, the aerosol removal is a function of electrical mobility, Z:

$$Z = qB,$$

where q = number of electrons on particle, and

B = aerosol mechanical mobility (given in discussion above on dry deposition/ diffusion).

B has a dependence on both the molecular mean-free path and viscosity. The value of B at a constant termperature, 20°C (293°K), will increase by 20 percent for 0.005 μm and 5 percent for 0.5 μm diameter particles in going from sea level to 1,524 m. However, if the temperature is -31°C (242°K) at 1,524 m, B is depressed with respect to values at sea level 20°C (293°K). The performance of the mobility analyzer is expected to be sensitive to altitude parameters, but due to the complexity of the calculations, no degree of deviation from performance at sea level is anticipated.

Aspiration inlets for aerosol sampling are known to have a variable efficiency for coarse particles (5). The performance of inlets at this time cannot be described exactly, but the same aerosol properties that govern dry depostion of fine and coarse aerosol are expected to govern inlet performance. It is expected that inlet performance at sea level and at 1,524 m is unity for particles with diameters less than 1 μm. The change in *stop distance* is used to estimate the change in performance at high and low altitudes. Since the *stop distance* is dependent upon the viscosity, but independent of air density, one would expect the coarse particle performance of inlets to depend only upon temperature. A lowering of the temperature from 20°C (293°K) to -31°C (242°K) increases the *stop distance* by about 20 percent, which implies qualitatively that the efficiency of an aspiration inlet will decrease as temperature decreases. Generally, it would be expected that the efficiency of the high volume sampler would be unity for fine aerosols at high and low altitudes, but its efficiency (less than unity) for coarse aerosol would be decreased as temperature decreased.

It should be recognized that certain devices (such as most single particle light-scattering instruments) that do not measure a resistance-to-motion parameter have the same calibration at both high and low altitudes. Care must be taken with nephelometric measurements in removing the air scatter, which is a function of air density. Condensation nuclei counters would be expected to have a slightly lower counting efficiency at higher altitudes, due to the decreased thermal conductivity of air at lower pressures.

REFERENCES

1. Fairbridge, R. W. (ed.). The Encyclopedia of Atmospheric Sciences and Astrogeology. Encyclopedia of Earth Sciences Series, Vol. II. Van Nostrand Reinhold Publishing Corp., New York, 1967.
2. Weast, R. C. Handbook of Chemistry and Physics, 57th Edition. CRC Press, Cleveland, 1976.
3. Bretsznajder, S. Prediction of Transport and Other Physical Properties of Fluids. Pergamon; Press, New York, 1971.
4. Hidy, G. M. and J. R. Brock. The Dynamics of Aerocollodial Systems. Pergamon Press, New York, 1970.
5. Fuchs, N. A. The Mechanisms of Aerosols. Pergamon Press, New York, 1964.
6. Strauss, W. Industrial Gas Cleaning. Pergamon Press, New York, 1966.
7. Friedlander, S. K. Smoke, Dust and Haze. John Wiley and Sons, New York, 1977, pp. 162-164.

APPENDIX B

OTHER SYSTEMS - HIGH ALTITUDES

Precise data on the potential scope of the problems due to carbon monoxide for high altitude residents and visitors are not available. Approximately 2.2 million people live at altitudes above 1,524 m in the United States. These figures do not present a complete picture of potential numbers of individuals who may be subjected to carbon monoxide at these altitudes because the tourist population in these areas is high in both summer and winter. Furthermore, proper tuning of automobiles for high altitude travel is uncommon and the influx of visitors with cars that emit carbon monoxide and other contaminants may prove to be an important factor in raising pollution exposure to an unacceptable point.

Ambient air standards set at sea level are not applicable for high altitude sites. The United States Environmental Protection Agency's (EPA) primary standards are expressed in milligrams per cubic meter of air. At 1,540 m, each cubic meter contains approximately 18 percent less air than at sea level. Therefore, allowable concentrations of carbon monoxide in air in a city like Denver will be 22 percent higher than at sea level (i.e., a 10-mg/m^3 maximal permissible 8-hour average is equivalent to 10 mg/m^3 at sea level but 11.8 mg/m^3 at Denver's altitude).

Carbon monoxide exposure may aggravate the oxygen deficiency at high altitudes. When high altitude and carbon monoxide exposure are combined (Table B-1), the effects are apparently additive. It should be noted that each of these, decreased P_{O_2} in the air and increased carboxyhemoglobin, produce different physiologic responses. They have different effects on blood P_{O_2}, on the affinity of oxygen for hemoglobin, on the extent of oxyhemoglobin saturation (carbon monoxide hypoxemia shifts the oxyhemoglobin dissociation curve to the left, and a decrease in P_{AO_2} shifts it to the right), and on ventilatory drive.

The most supportive information on the additive nature of CO hypoxia and hypoxic hypoxia originates from psychophysiologic studies, and even these are not as persuasive as one would desire. Blackmore (1) analyzed the cause of aircraft accidents in Britain and found that carboxyhemoglobin levels provided valuable information relative to altitude and CO sources. The relatively high levels found could be attributed to equipment failure, smoking, and fires. No data are available on the effects of carbon monoxide on native inhabitants of high altitude or on the reactions of these natives when they are suddenly removed to sea level and possible high ambient carbon monoxide concentrations.

TABLE B-1. APPROXIMATE PHYSIOLOGICALLY EQUIVALENT ALTITUDES AT EQUILIBRIUM WITH AMBIENT CO LEVELS

Ambient CO Concentration		Actual Altitude (meters)		
mg/m^3	ppm	0 (sea level)	1,524	3,048
		(Physiologically Equivalent Altitudes with COHb)		
0	0	0 (sea level)	1,524	3,048
28.6	25	1,829	2,530	3,962
57.3	50	3,048	3,658	4,694
114.5	100	3,749	4,663	5,486

McFarland *et al.* (2) showed that changes in visual threshold occurred with carboxyhemoglobin as low as five percent or a simulated altitude of approximately 2,425 m. Halperin *et al.* (3) further noted that recovery from the detrimental effects on visual function lagged behind the elimination of carbon monoxide. However, the data given were sparse and the variability among the few subjects and the day-to-day variation were not given. Vollmer *et al.* (4) studied the effects of carbon monoxide at simulated altitudes of 3,070 and 4,555 m and reported that there were no additive effects of carbon monoxide and altitude. They suggested that the effects of carbon monoxide were masked by some compensatory mechanisms. The data presented were not convincing. Lilienthal and Fugitt (5) indicated that the combination of altitude (1,540 m) and a five to nine percent carboxyhemoglobin induced a decrease in flicker fusion frequency, although neither one alone had an effect. They also reported that the presence of 8 to 10 percent carboxyhemoglobin was effective in reducing altitude tolerance by some 1,215 m. Forbes *et al.* (6) found that, during light activity at an altitude of 4,875 m, carbon monoxide uptake was increased, probably owing to the hyperventilation caused by the respiratory stimulus of decreased P_{O_2}. Evidence that

CO elimination was similiar at sea level and at altitudes up to 10,000 m was obtained by several investigators. (7,8) Increased ambient temperatures up to 35°C and hard physical work increased the rate of elimination. (4) Pitts and Pace (9) stated that every one percent increase in carboxyhemoglobin (up to 13 percent) was equivalent to a 109-m rise in altitude if the subjects were at altitudes of 2,100 to 3,070 m. Their observations were based on changes in the heart rate response to work. Subjects who may have been smokers were not identified.

Two groups of investigators have presented data comparing the physiologic responses of subjects to altitude and carbon monoxide where the hypoxemia due to altitude and the presence of carboxyhemoglobin were approximately equivalent. In one study, (10) the carboxyhemoglobin varied around 12 percent (although the mode of presentation of carbon monoxide was such that carboxyhemoglobin ranged from 5 to 20 percent during the carbon monoxide exposures) and the altitude study was conducted at 3,977 m. The second study (8) compared responses of altitudes of 4,000 m and a carboxyhemoglobin content of 20 percent. In both these studies, carboxyhemoglobin content was in excess of that anticipated for typical ambient pollution. However, it was suggested that the effects attributable to carbon monoxide and to altitude were equivalent.

It was recommended on theoretical grounds that the ambient carbon monoxide in tunnels being constructed at 3,859 m should not exceed 29 mg/m^3. (11) The maximal aerobic capacity is reduced approximately 20 percent in individuals exposed to an altitu le of 3,085 m. Weiser *et al.* (12) reported that max V_{O_2} was significantly impaired in subjects living at 1,700 m when their COHb levels were five percent. However, this decrement is similar to that seen in sea level residents. No data are available for higher altitudes. Brewer *et al.* (13) conducted a study on residents of Leadville, Colorado (3,085 m). The mean COHb level in smokers at this altitude was higher than that of smokers at sea level. This increased degree of hypoxemia may have contributed to the elevated red cell mass observed, since individuals who stopped smoking demonstrated a reduction in their red cell mass.

The most important information regarding carbon monoxide exposures and altitudes, the preciseness of their potentially additive effects., has not received much attention, and what little information there is has been obtained by assuming simple additive effects. (14) It has not been verified by direct experiments.

Recently reported epidemiological data indicate a correlation between complaints of cardiorespiratory problems and ambient CO levels in Denver residents. The results suggest there is a threshold effect at levels lower than had been previously suggested. (15, 16).

REFERENCES

1. Blackmore, D. J. Aircraft Accident Toxicology: U.K. Experience 1967-1972. Aerosp. Med. *45*:987-994, 1974.
2. McFarland, R. A., F. J. W. Roughton, M. H. Halperin, and J. I. Niven. The Effects of Carbon Monoxide and Altitude on Visual Thresholds. J. Aviat. Med. *15*:381-394, 1944.
3. Halperin, M. H., R. A. McFarland, J. I. Niven, and F. J. W. Roughton. The Time Course of the Effects of Carbon Monoxide on Visual Thresholds. J. Physiol. (London) *146*:583-593, 1959.
4. Vollmer, E. P., B. G. King, J. E. Birren, and M. B. Fisher. The Effects of Carbon Monoxide on Three Types of Performance at Simulated Altitudes of 10,000 and 15,000 Feet. J. Exp. Psychol. *36*:244-251, 1946.
5. Lilienthal, J. L., Jr. and C. H. Fugitt. The Effect of Low Concentrations of Carboxyhemoglobin on the "Altitude Tolerance" of Man. Am. J. Physiol. *145*:359-364, 1946.
6. Forbes, W. H., F. Sargent, and F. J. W. Roughton. The Rate of Carbon Monoxide Uptake by Normal Men. Am. J. Physiol. *143*:594-608, 1945.
7. Gordinsky, S. M., A. V. Sedov, A. N. Mazin G. A. Gaziev, A. P. Kleptsova, and L. I. Zhukova. Effect of Reduced Barometric Pressure on the Elimination of Gaseous and Volatile Metabolites of Suited Man. Cosm. Biol. Med. *2*:78-82, 1970.
8. Sedov, A. V., L. I. Zhukova, and G. E. Mazneva. Carbon Monoxide Excretion by the Human Organism. Gig. TR. Prof. Zabol *15*:36-39, 1971.
9. Pitts, G. C. and N. Pace. The Effect of Blood Carboxyhemoglobin Concentration on Hypoxia Tolerance. Am. J. Physiol. *148*:139-151, 1947.
10. Oski, F. A. and A. A. Altman. Carboxyhemoglobin Levels in Hemolytic Disease of the Newborn. J. Pediatr. *61*:709, 1962.
11. Miranda, J. M., V. J. Konopinski, and R. I. Larsen. Carbon Monoxide Control in a High Highway Tunnel. Arch. Environ. Health *15*:16-25. 1967.
12. Weiser, P. C., C. G. Morrell, D. W. Dickey, T. L. Kurt, and G. J. A. Cropp. Effects of Low-Level Carbon Monoxide Exposure on the Adaptation of Healthy Young Men to Aerobic Work at an Altitude of 1610 Meters. *In*: Environmental Stress: Individual Adaptation. Folinsbee, L. J. (ed.), Academic Press, New York (In Press).
13. Brewer, G. J., C. F. Sing, J. W. Eaton, J. V. Weil, L. F. Brewer, and R. F. Grover. Effects of Hemoglobin Oxygen Affinity of Smoking in Residents of Intermediate Altitude. J. Lab. Clin. Med. *84*(2):191-205, 1974.
14. Howlett, L. and R. J. Shepard. Carbon Monoxide as a Hazard in Aviation. J. Occup. Med. *15*:874-877, 1973.
15. Kurt, L., R. P. Mogielnicki, and J. E. Chandler. Association of Acute Cardiorespiratory Complaints with Ambient Levels of Carbon Monoxide. Chest *74*:10-14, 1978.
16. Aronow, W. S. Effect of Ambient CO on Cardiopulmonary Disease. Chest *74*:1-2, 1968.